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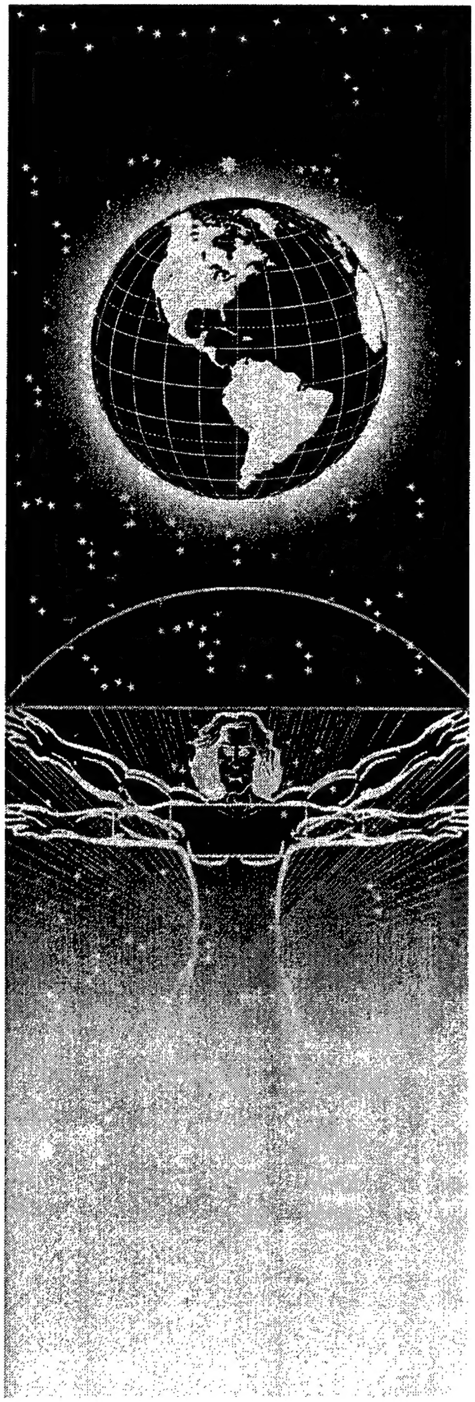

UNITED STATES AIR FORCE RESEARCH LABORATORY

AEROSPACE TRANSPARENCY RESEARCH COMPENDIUM

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FOR THE COMMANDER

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13. ABSTRACT *(Maximum 200 words)*

For nearly 30 years, the Crew System Interface Division (HEC; www.hec.afrl.af.mil) of the Air Force Research Laboratory (AFRL), located at Wright-Patterson AFB OH, has advanced aerospace transparency technology through the investigative research of numerous optical and visual parameters inherent in aerospace transparencies. This document contains reprints of four publications by AFRL/HEC, which provide an overview of various optical characteristics, visual effects and other issues associated with aircraft transparencies. Also included is an annotated bibliography of in-house publications, a bibliography of additional transparency-related publications plus listings of standardized test methods and related patent abstracts.

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INTRODUCTION

In the early part of the 1970s, F-111 aircraft began flying low altitude missions at high speeds and subsequently encountered an increase in the incidence of bird strikes. The original F-111 windscreens were constructed of relatively thin glass, which provided essentially no bird-strike protection. To address this problem, a Bird Impact Resistant Transparency (BIRT) windscreen was developed that incorporated multiple layers of laminated plastic. While these BIRT windscreens performed very well as protection against bird strikes, they also introduced an entirely new set of optical and visual effects that interfered with aircrew visual performance. Multiple imaging was one of the first issues raised by aircrew. This phenomenon is only visible at night when viewing certain light sources, such as runway marker lights. The effect of multiple imaging is the presence of secondary, and sometimes tertiary, images of the light source. This effect can cause some confusion when aircrew perform certain flight operations at night. One anecdotal pilot comment was "which set of runway lights do I use to land?" In addition to multiple imaging, several other effects were noted including distortion, contrast loss due to haze, reflections, birefringence (rainbowing), and reduced light transmission. Previously, these effects were not manifested in glass windscreens. Consequently, there were no measurement procedures, specification values, or means of relating the severity of these effects to human visual performance. In 1974, it became one of the missions of the Human Engineering Division, of what was then the Aerospace Medical Research Laboratory (AMRL) at Wright-Patterson AFB, Ohio, to address these optical and visual effects in conjunction with the windscreen and airframe manufacturing community. This was the beginning of the windscreen evaluation facility developed at AMRL, currently the Human Effectiveness Directorate of the Air Force Research Laboratory.

For almost 30 years, the Visual Image Evaluation of Windscreens (VIEW) facility has developed methods and instrumentation to characterize and measure optical and visual effects of most fixed-wing aircraft transparency systems. Psychophysical studies were conducted to relate various optical characteristics to human visual performance. Results of these measurements and studies were used to develop test methods and acceptance criteria used in transparency manufacturing. The majority of this work was performed in cooperation with the American Society for Testing and Materials (ASTM) subcommittee F7.08 on Aerospace Transparency Enclosures. Many of the methods developed by the windscreen evaluation facility have become ASTM standardized test methods or practices. In addition, many of the optical test devices and procedures developed in the VIEW facility were patented by the US Air Force.

This document provides a compilation of windscreen evaluation activities performed by this and other related organizations. Four publications that provide an overview of windscreen technology are reprinted in their entirety. Grether (1973), published before the establishment of the windscreen evaluation facility, provides a synopsis of many optical visual effects and issues associated with aircraft transparencies. Barbato, Hausmann, Kama, Bridenbaugh and Task (1993) provides definitions of terms used in the windscreen area. Merkel and Task (1989) is an illustrated guide to the optical and visual effects that have been encountered. LaPuma and Bridenbaugh (1988) is a technical

report that summarizes several of the optical and visual specification values that have been used over the years for many military aircraft.

The next section of this document is an annotated bibliography that lists the unlimited distribution publications produced by members of the windscreen evaluation facility. Following that section is a bibliography of related publications in the windscreen technology area. The last two sections list the ASTM standardized test methods and practices that relate to the windscreen area and abstracts of patents that have been issued to the US Air Force relating to the windscreen evaluation facility team activities.

This document serves as a guide and reference for those who are involved in evaluating optical and visual parameters of aircraft transparency systems.

Grether, W. F. (1973). ***Optical factors in aircraft windshield design as related to pilot visual performance.*** (Report No. AMRL-TR-73-57). Wright-Patterson AFB, OH: Aerospace Medical Research Laboratory. (DTIC No. AD767203).

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OPTICAL FACTORS IN AIRCRAFT WINDSHIELD DESIGN AS RELATED TO PILOT VISUAL PERFORMANCE

WALTER F. GRETHER

JULY 1973

Approved for public release; distribution unlimited.

AEROSPACE MEDICAL RESEARCH LABORATORY
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
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FOR THE COMMANDER

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13. ABSTRACT

The slope and curvature of aircraft windshields that are optimum for high speed flight cause optical degradation of pilot vision in the forward direction. This report presents a survey of the literature bearing on the conflict between aerodynamic and visual requirements. The optical effects of windshield slope (or angle of incidence) and curvature are reviewed, in terms of displacement, deviation, distortion, binocular deviation, reflections, multiple images, haze, transmission loss, and reduced resolution. Included in the review are discussions of windshield design practices in recent military aircraft, as well as optical standards and tolerance contained in current military specifications. The review also provides a discussion and research data on pilot visual performance as affected by windshield design factors, and a small sample of pilot opinions concerning the visual problems caused by the windshield of the F-111 aircraft. The report concludes with some suggestions for further studies that would assist in making choices concerning windshield design.

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PREFACE

This report was prepared at the suggestion of Col Neville P. Clarke, Director of Research and Development, Headquarters Aerospace Medical Division, Brooks AFB, Texas. His suggestion resulted from increasing pilot complaints of visual problems caused by the windshield of the F-111 aircraft, from questions about pilot visual capabilities arising during the development of the windshield for the B-1 aircraft, and other indications of pilot visual problems related to windshield design. The work of preparing the report was carried out under Project 7184, Human Engineering for Air Force Systems.

For their valuable technical assistance in preparation of this report, the author is particularly grateful to the following persons: Mr. Robert E. Wittman and Capt Donald C. Chapin of the Improved Windshield Development, Advanced Development Program Office, USAF Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio; Col Benjamin Kislin and Capt Wayne Provines of the Opthalmology Branch, School of Aerospace Medicine, Brooks AFB, Texas; and Dr. Celtus J. Muick and Mr. Tung Sheng Liu, Deputy for Engineering, Aeronautical Systems Division, Wright-Patterson AFB, Ohio. Mrs. Joan C. Robinette of the Technical Information Office, of this Laboratory, was most helpful in obtaining some of the literature and in the editing and publication of the report.

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1. INTRODUCTION AND PURPOSE

Good vision for the pilot in the forward direction is a normal design requirement for all aircraft. It is a requirement, however, that has been increasingly difficult for the aircraft designer to achieve as flight speeds have increased. The basis for this conflict in design requirements is quite simple and well known. Optimum visibility calls for a flat windshield installed very nearly perpendicular to the pilot's line of sight. High speed flight, on the other hand, calls for a windshield that is thick, multilayered, coated for various purposes, curved, and slanted backward at a very shallow angle. All of these optical features produce unfavorable effects on vision.

The problem of providing good forward visibility becomes particularly critical in the design of supersonic aircraft. For supersonic transports the use of a hinged nose section permits good pilot visibility during takeoffs and landings. But during other regimes, when the nose is in the up position, forward vision is considerably degraded (Larry, 1966). About twenty years ago much thought was given by research and design personnel to the possible substitution of a periscope for the windshield in supersonic aircraft. Flight research by Roscoe and his associates (1951, 1966) demonstrated that pilots could take off, fly, and land an aircraft using only a periscope for forward vision. But, as a solution to the windshield problem for highspeed aircraft, the periscope never appeared to be acceptable. The visual problems inherent in the use of periscopes and other windshield substitutes in aircraft are discussed by Wulfeck et al. (1958). A recent paper by Beaumont (1973) describes some new periscope concepts that might make the periscope an acceptable alternative.

For military aircraft, even those designed for supersonic speeds, no use has been made of the hinged nose, periscope, or other similar innovation as a means of achieving good forward visibility. As a consequence, the windshields of high performance military aircraft, to varying degrees, have handicapped the pilot's forward vision. The difficulties experienced by pilots are discussed later in this report.

It might be argued that the needs for good forward visibility are no longer important because of modern reliance on ground control of air traffic, and the instruments, radar, and radio aids now available to flight crews. While it is true that the reliance on vision outside the aircraft has been reduced for some aspects of flight, forward vision is still of major importance. Aside from the pilot's natural desire to see ahead and be assured of clear passage, there are many pilot duties requiring good forward vision. The most critical of these for military aircraft are probably taxi, landing, in-flight refueling, collision avoidance, formation flying, and detection and sighting of tactical ground and air targets.

This report presents a literature survey of optical factors in aircraft windshield design and relates them to modern Air Force requirements for pilot's vision in the generally forward direction. The survey covers research and technical literature bearing on this subject. It also discusses current military specifications, requirements, design practices, and optical test methods. It is hoped that the information provided in this review will be helpful to persons responsible for windshield design in future military aircraft. This report is limited to the problems of pilot vision through the transparent portion of the forward windshield. There are many other important problems of vision from aircraft, such as overall fields of view and obstructions to vision, which are not covered or

only touched on lightly. For information about these and other problems of pilot vision the reader is referred to the report, *Vision in Military Aviation,* by Wulfeck et al. (1958).

Very helpful to the author in preparing this review were a number of general review articles and reports bearing on the problems of visibility through aircraft windshields (Cocagne and Blome, 1968; Corney, 1973; Corney and Shaw, 1971; Glover, 1955; Grether and Muick, 1964; Holloway, 1970; Pinson and Chapanis, 1946; and Provines and Kislin, 1971.

2. WINDSHIELD GEOMETRY

Two aspects of windshield geometry are of particular importance in terms of their effects on pilot vision. These are angle of incidence and radius of curvature. Angle of incidence is measured with respect to the pilot's horizontal sighting line and a line normal to the windshield surface (see Fig. 1A). A high angle of incidence is generally desirable for aerodynamic reasons to achieve minimum disturbance of the airflow along the fuselage.

Windshields may be either flat or curved panels or a combination of these. Amount of curvature is defined in terms of the radius of the curvature. If the curvature is about one axis and the surface represents a section of a cylinder, it is referred to as single curvature. The surface may also represent a section of a sphere or other complex shape so as to conform with the adjacent aerodynamic shape, and is referred to as having double or compound curvature. Curved windshield panels in military aircraft quite often represent a section of a cone, thus having a range of curvatures about a single axis.

The use of curvatures is aerodynamically beneficial. It also makes possible what might be called a wrap-around effect, giving a larger forward view without visual obstruction by supporting members. In fighter aircraft, a fairly standard windshield has consisted of a flat, sloping front panel, with two curved side panels. With this design, of necessity, there are obstructions to vision by the framing that joins the front and side panels. However, if the frame members are narrower than the distance between the two eyes (about 2.25 in.) there are no areas in which vision is completely cut off. By using curved windshields in single place or tandem aircraft, one wrap-around panel can replace the combination of a flat front and two curved side panels. Such a one-piece windshield has the advantage of providing a larger clear field of view, but introduces some very undesirable optical effects.

3. DEFINITION OF OPTICAL TERMS AND THEIR EFFECTS ON VISION

To provide a basis for the material which follows, this section describes the optical effects that will be discussed, and shows how they interrelate with each other. Many of these effects are illustrated in Fig. 1. For purposes of illustration the effects are considerably exaggerated. Also, the effects are illustrated for simple single-layer windows, rather than laminated transparencies as

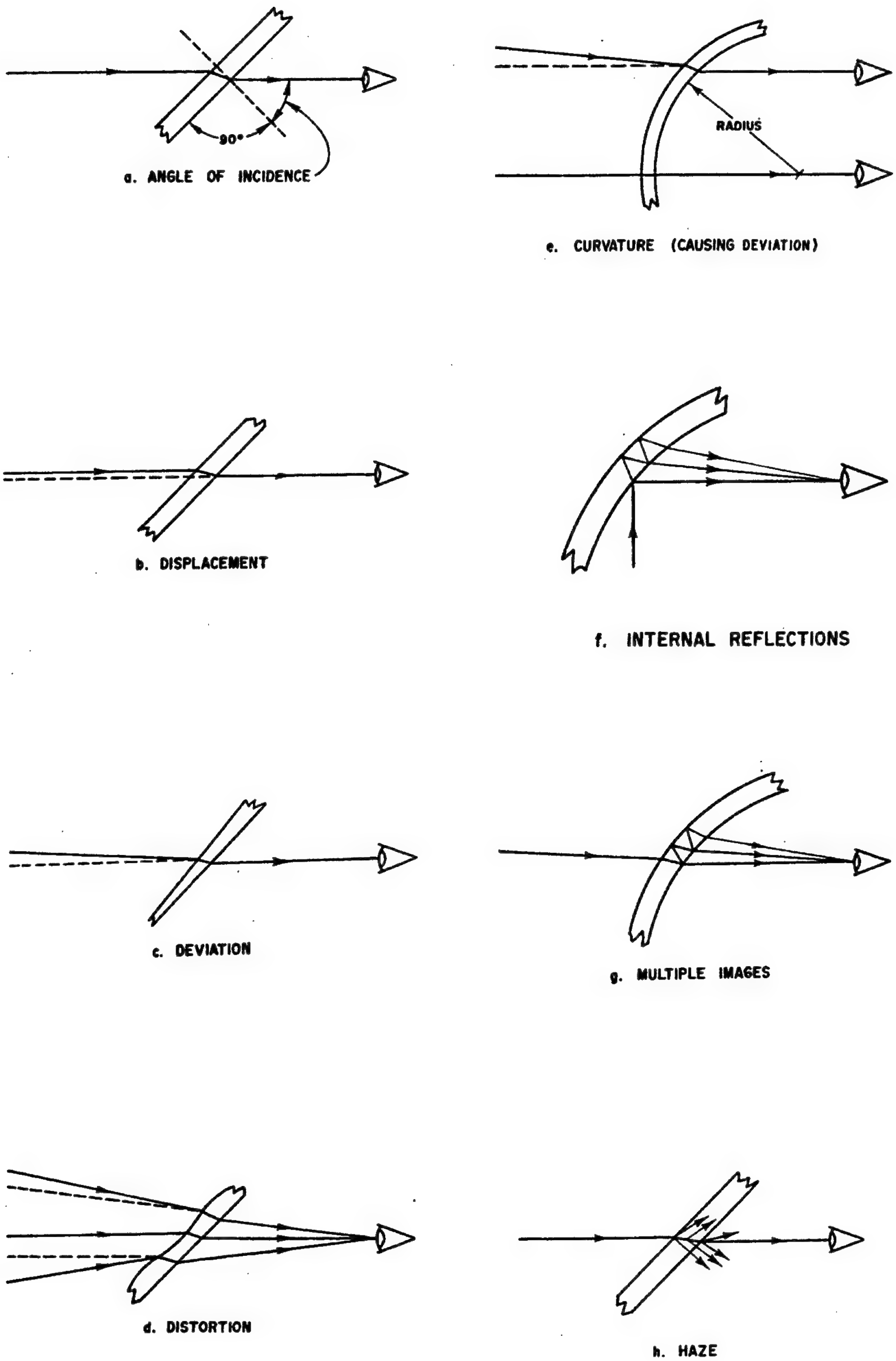

Figure 1. Optical effects related to aircraft windshield design.

normally used in windshields. Each layer of a laminated transparency can contain any or all of the optical effects shown.

A. ANGLE OF INCIDENCE

(See preceding section and Fig. 1A.)

B. DISPLACEMENT

In passing through a window with parallel surfaces, light rays are bent and displaced as shown in Fig. 1B. The displacement is zero for 0° angle of incidence, and increases as the angle of incidence, thickness, or index of refraction are increased. The displacement is linear and usually measured in millimeters or fractional inches. It does not increase with distance and the effect on pilot vision probably is not significant.

C. DEVIATION

In passing through a window with nonparallel (wedge) surfaces the path of light is deviated angularly as shown in Fig. 1C. The amount of deviation is expressed in terms of the angular change (degrees, minutes, or seconds.) Deviation increases with index of refraction of the window material, the amount by which the surfaces deviate from parallelism, and the angle of incidence. Deviation causes objects to be seen at other than their true direction from the observer (pilot).

D. DISTORTION

If a window has minor variations in thickness, or in parallelism of the two surfaces, there will be variations in deviation for different parts of the window (see Fig. 1D). This effect will cause straight lines to appear wavy, and the shapes of objects to appear distorted. As moving objects are seen through different parts of the window their motion and shape will change irregularly. Distortion increases with index of refraction and angle of incidence. Also, curved windows normally cause much more distortion than flat windows. The measurement and quantification of distortion are discussed later.

E. CURVATURE

Light rays passing through curved glass at zero angle of incidence to the radius of curvature will enter and exit with no deviation of the light path (see Section 2 and Fig. 1E). For all other angles of incidence relative to the radius of curvature the light will exit with some deviation, even though the surfaces are perfectly concentric. The deviation increases with increasing angle of incidence, index of refraction, thickness of the transparency, and with decreasing radius of curvature.

F. INTERNAL REFLECTIONS

Lights or bright objects inside the crew station can be reflected into the pilot's eyes from the inside surface of a window (see Fig. 1F). Under many circumstances, ground lights, such as lights from a city, will also reflect from the inside windshield surface into the pilot's eyes. Such internally reflected images will appear superimposed over the area seen through the windshield, and therefore will obscure vision for objects outside. These internally reflected images are normally troublesome only under night conditions. Under particular conditions these reflections may be multiple, as in the case of multiple images discussed below.

G. MULTIPLE IMAGES

On passing through a window, some light is reflected at each surface as the light enters and leaves. The proportion reflected is minimal at zero angle of incidence, and increases to 100% as the angle approaches 90°. Under some optical conditions the reflections inside the transparency may result in one or more secondary images, as illustrated in Fig. 1G. For a laminated panel there may be additional images caused by reflections at the laminations. Since these secondary or ghost images are less bright than the primary image, they are normally seen and become a problem only at night. The optical conditions most likely to produce multiple images are curved panels, or flat panels with wedginess, combined with high angles of incidence. A metallic coating on the transparency increases the intensity of the secondary images. Such multiple images will occur with flat panels only if there is sufficient wedginess to reflect the displaced image or images back to the observer's eyes, rather than along a path parallel to the exit path of the primary image. Multiple images can normally be avoided by use of high quality flat panels.

H. BINOCULAR DEVIATION

If there is curvature in the horizontal plane, the deviation due to curvature will be different for the two eyes (as shown in exaggerated form in Fig. 1E), since the two eyes see through different parts of the curved window. This causes an effect called binocular deviation (Corney and Shaw, 1971; and Corney, 1973). It is believed that the eyes can readily adjust to small amounts of binocular deviation. However, when the collimated image of a gunsight or heads-up display is superimposed over the view through a curved windshield the binocular images may not be compatible (see section 6, also Fisher, 1973). Curved windows are more difficult to manufacture than flat windows, and therefore more likely to have defects causing deviation and distortion, which also will cause binocular deviation effects. These will vary for different parts of the windshield.

I. HAZE

As light enters or passes through a window some of the light may be scattered and appear as haze or fog in the window (see Fig. 1I). Such haze is increased by dirt, scratches, or abrasions on the window surface. Haze is generally defined in terms of the percent of light scattered and therefore lost in passage through the window. The haze effect is increased as the angle of incidence is increased. It is minimized if windshields are clean and free of abrasions. Haze contributes greatly to glare when looking toward the sun or other high intensity light sources. It also reduces the contrast of objects seen through the windshield.

J. TRANSMISSION

Some light is lost by absorption within the transparent material. This normally is a rather small percentage of the light, except for very thick windows. In aircraft windshields the use of electrically conductive and radar reflective coatings contribute to light loss by absorption. Most of the transmission loss is due to reflections, and this loss increases with angle of incidence. Most important, however, is the total light transmitted, regardless of whether the loss is due to surface reflections, haze or absorption. Transmission is measured in terms of the percent of incident light that reaches the observer. During daytime reduced transmission is quite tolerable and even desirable. At night, when vision is already marginal, reduced light transmission will further reduce the visual capacities of the pilot or other observer.

K. RESOLUTION

Resolution refers to visual acuity, or the ability of the observer to resolve fine detail. Under

typical daytime conditions, using a rough rule of thumb, a person with normal vision can resolve lines separated by one minute of arc. A windshield may cause some loss of resolving power, particularly if dirty, scratched, or of poor quality material. Some of the factors discussed earlier, namely haze and reduced transmission, are the major factors affecting visual acuity of the observer in looking through a window.

4. WINDSHIELD DESIGN PRACTICES WITH REGARD TO ANGLE OF INCIDENCE AND CURVATURE

In terms of its effect on pilot vision, angle of incidence is one of the two most important optical parameters in windshield design. The other critical design factor is use of curved versus flat panels. Based upon studies conducted during World War II (Pinson and Chapanis, 1946), the windshield design standards for many years set the maximum angle of incidence at 60°, and required the use of flat panels. As aircraft speeds have increased, the Air Force has permitted higher angles of incidence and the use of curved windshield panels.

The current Air Force Systems Command Design Handbook (AFSC-DH-2-1, DN 3A1, 1 October 1969) requires "that the angle of incidence throughout the windshield panel does not exceed 60°." Similarly, the US Navy (Mil-W-81752(AS), 23 April 1970) states that "in no case shall the angle of incidence exceed 60° for a line of vision from the pilot's eyes to any point in the transparent area used during approach and landing as required by MIL-STD-850." Both of these design specifications, as written, set the maximum angle at 60°, not only for the horizontal line of sight, but for all parts of the forward windshield.

Angle of incidence requirements are also provided in MIL-STD-850B, dated 3 November 1970, as follows, "at the intersection of the horizontal vision line and the windshield, the angle of incidence shall not exceed 60°." This specification does not prohibit a larger angle of incidence in other than the forward central portion of the windshield. Also provided in MIL-STD-850B are requirements for visual clear areas to be provided. For the pilot position in single and tandem fighter/attack aircraft, at zero degrees azimuth, there is a requirement for 11° downward and 10° upward vision. For side-by-side fighter/attack aircraft these requirements are 13° downward and 12° upward. For bomber/transport aircraft they are 17° downward and 20° upward. Using these requirements for downward vision, and the angle of incidence requirements of MIL-W-81752, the horizontal angle of incidence requirements are 49° for tandem and single-place fighter/attack, 47° for side-by-side fighter/attack, and 43° for bomber/transport aircraft.

Table 1 provides data on angle of incidence and curvature of windshields in some of the recent Air Force and Navy aircraft. It is apparent from this table that the Navy continues to prefer flat windshield panels, and retains angles of incidence to the horizontal sight line of 60° or less. By comparison, the Air Force, for some of the newer aircraft, has chosen curved windshields, with angles of incidence considerably exceeding the 60° standard. It would appear from this difference in design practices that the Navy places a higher premium on pilot vision requirements because of the need for visually guided landings on aircraft carriers. This would seem to be the major difference between the Navy and Air Force in demands on pilot vision.

TABLE 1. WINDSHIELD GEOMETRY OF SOME RECENT MILITARY AIRCRAFT*

Aircraft Type No.	General Windshield Configuration	Horizontal Angle of Incidence	Downward Vision Angle at 0 Azimuth	Radius of Curvature
F-4	Flat front plus two curved side panels	62°	15°	Flat
F-14	Flat front plus two curved side panels	60°	15° 38′	Flat
A-7	Flat front plus two curved side panels	60°	15° 45′	Flat
AX (A-10)	Flat front plus two curved side panels	45°	20°	Flat
F-106	V-type, two panels	70°+	15°–17°	Flat
F-111	V-type, two panels	68.4°	11.5°	18–31 in.
B-1	V-type, two panels	65°	15°	50 in.
T-38	One-panel	62.5°	11.5°	13.2–16.4 in.
F-5	One-panel	66°	11°	14.3–16.0 in.
F-15	One-panel	62°	15°	16–18 in.

*These data were provided by Robert E. Wittman, of the Improved Windshield Development, Advanced Development Program Office, USAF Flight Dynamics Laboratory, Wright-Patterson AFB.

5. OPTICAL EFFECTS OF ANGLE OF INCIDENCE

As the angle of incidence is increased, a number of optical effects occur that are unfavorable to vision. Some of these effects are caused by the increased thickness of the transparent material through which the light must pass. Other effects are due to a greater proportion of the light being reflected at the surfaces, including surfaces of laminations. The most serious effects, however, result from magnification of deviation and distortion caused by wedginess and irregularities in the surfaces of the window.

Shown in Fig. 2 are the changes in deviation and distortion with angle of incidence. The data on deviation are from AFSC Design Handbook 2-1, and the data on distortion from Cocagne and Blome (1968). The curves show the multiplication factors by which the value at zero angle of incidence is increased. If, for example, a piece of glass caused a deviation of 10 minutes of arc at zero angle of incidence, this value would be increased to approximately 50 minutes of arc at 70°. For distortion the curve is read in the same manner, except that the measurement is in terms of maximum line slope change on a rectangular grid photographed through the test window.

Similar data on effects of angle of incidence are shown in Fig. 3 for surface reflections, and for transmission through a window (from AFSC Design Handbook 2-1). The reflection data apply to the surface where light enters a window. For reflections inside the window, at the surface where light exits, the same data apply, but only to the angle of light rays before entering the window. For light rays inside the window the curve is shifted to the left by an amount depending on the index of refraction of the material. The transmission losses shown in Fig. 3 are due, in large part, to the light lost by reflection.

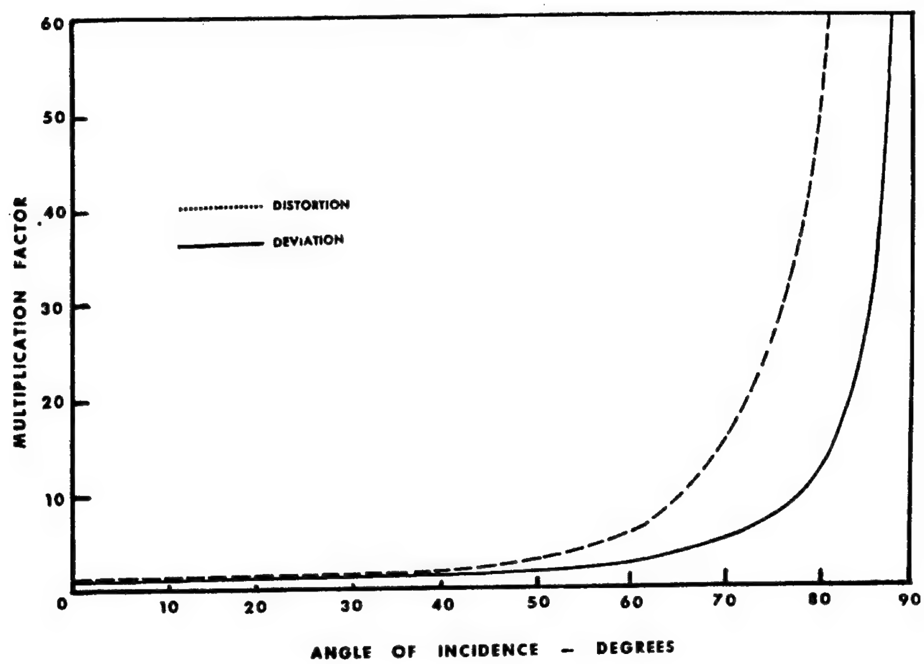

Figure 2. Effects of angle of incidence on optical deviation (from AFSC Design Handbook 2–1, 1969) and distortion (from Cocagne and Blome, 1968).

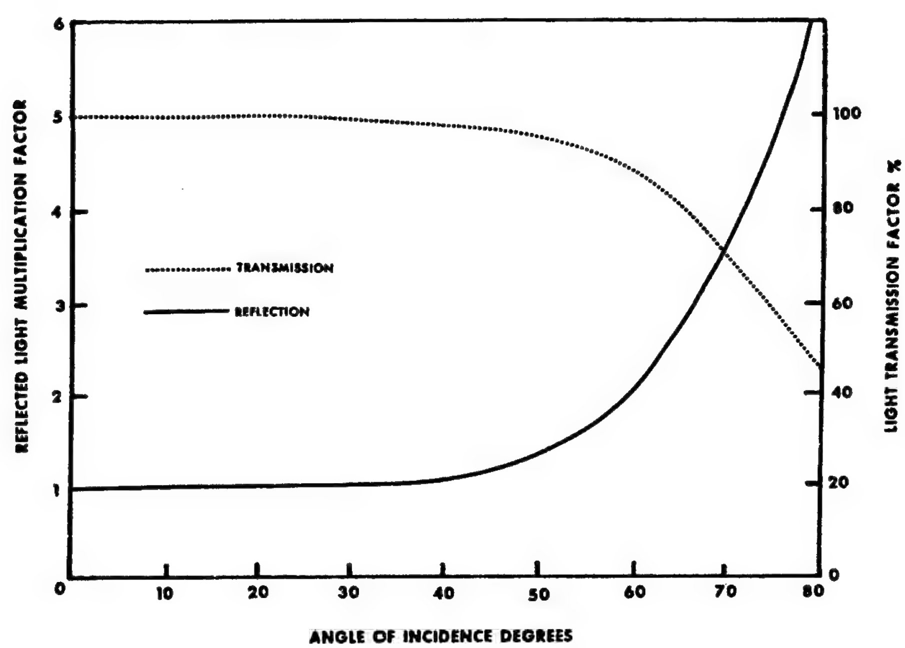

Figure 3. Effects of angle of incidence on surface reflections and transmission loss (from AFSC Design Handbook 2–1, 1969).

All four curves shown in Fig. 2 and 3 have basically the same form, and show that deviation, distortion, reflections, and transmission loss all increase rapidly as the angle of incidence exceeds 60°. For all curves, the change between 60° and 70° is greater than that between 0° and 60°. It is primarily from these data that the design standards referred to earlier were derived, which set 60° as the maximum allowable angle of incidence for military aircraft windshields.

6. OPTICAL EFFECTS OF CURVATURE

As shown in Fig. 1E, a light ray passing through a curved window at other than zero angle of incidence with reference to the radius of curvature, will be given some angular deviation, even though there are no defects and the window surfaces are perfectly concentric. In addition to the angle of incidence, the amount of this deviation depends upon the radius of curvature, the thickness of the window, and the index of refraction. If a pilot's eye position is at the radius of curvature of a curved windshield, he will experience no deviation caused by the curvature itself. Most likely there will be deviation from wedginess in the transparency, since it is much more difficult to avoid such defects in curved as opposed to flat windows.

The extent to which deviation is affected by radius of curvature and angle of incidence is illustrated by data from Pinson and Chapanis (1946) shown in Fig. 4. In these curves thickness and index of refraction are held constant. More commonly such data are plotted in terms of the ratio of thickness to radius of curvature (thickness ratio) rather than radius alone. Such a plot is shown in Fig. 5, using data from Holloway (1970). As can be seen from these curves, a combination of a thick window (as used in aircraft windshields), high angle of incidence, and short radius of curvature can result in very high angles of deviation. It is very important, therefore, where curved windshields are used, to keep the radius of curvature as large as possible, and to position the windshield so that the pilot's eyes will be near the center of the curvature. In addition, the curvature should be single rather than compound.

Another undesirable optical effect caused by curvature is the production of multiple images, as shown in Fig. 1G. With flat panels, having parallel surfaces, the internally reflected rays exit in parallel with the primary ray, and thus are not seen. With a curved or distorting window, however, the internally reflected rays exit at a different angle from the primary ray, and may converge with it at the observer's eye. This causes the observer to see the same object or light source at two or more locations. Such multiple images are most likely to occur at large angles of incidence and high thickness-curvature ratios. Also, the images are increased in brightness and separation as the angle of incidence is increased.

Reflections from the inner surface of a windshield, from lights or lighted objects in the cockpit, are much more troublesome with curved panels. With flat sloping windshields, combined with a glare shield, most such reflections can be prevented from reaching the pilot's eyes. Curved panels provide many more possible reflection angles, thus increasing the potential light sources that may be seen reflected from the windshield.

The most critical sighting area in a fighter-type aircraft is the central portion of the windshield, which is used in conjunction with the reflector-type of gunsight. For aircraft using such a sight a

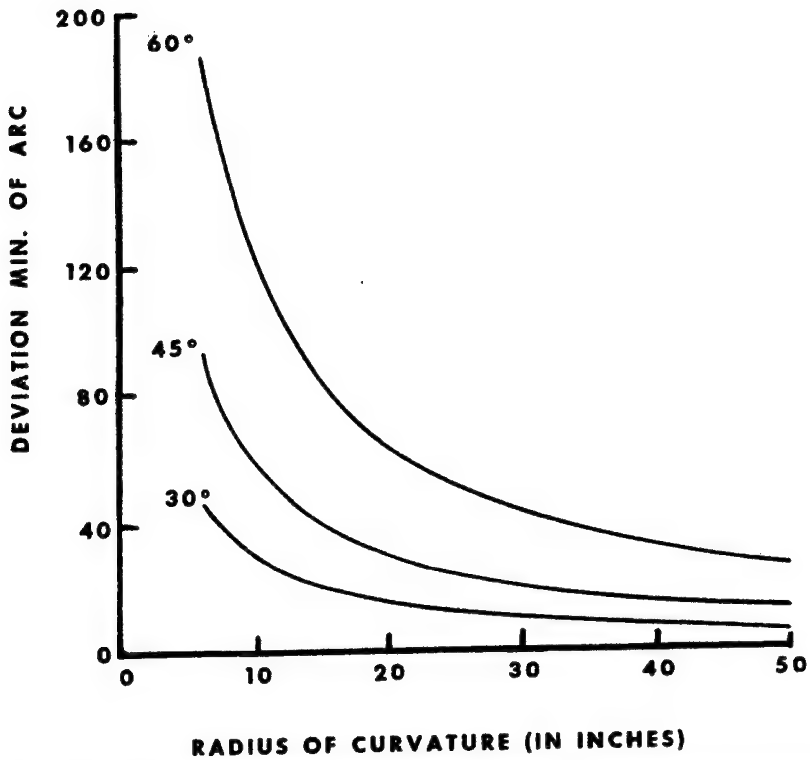

Figure 4. Effects of radius of curvature on optical deviation at three angles of incidence (from Pinson and Chapanis, 1946).

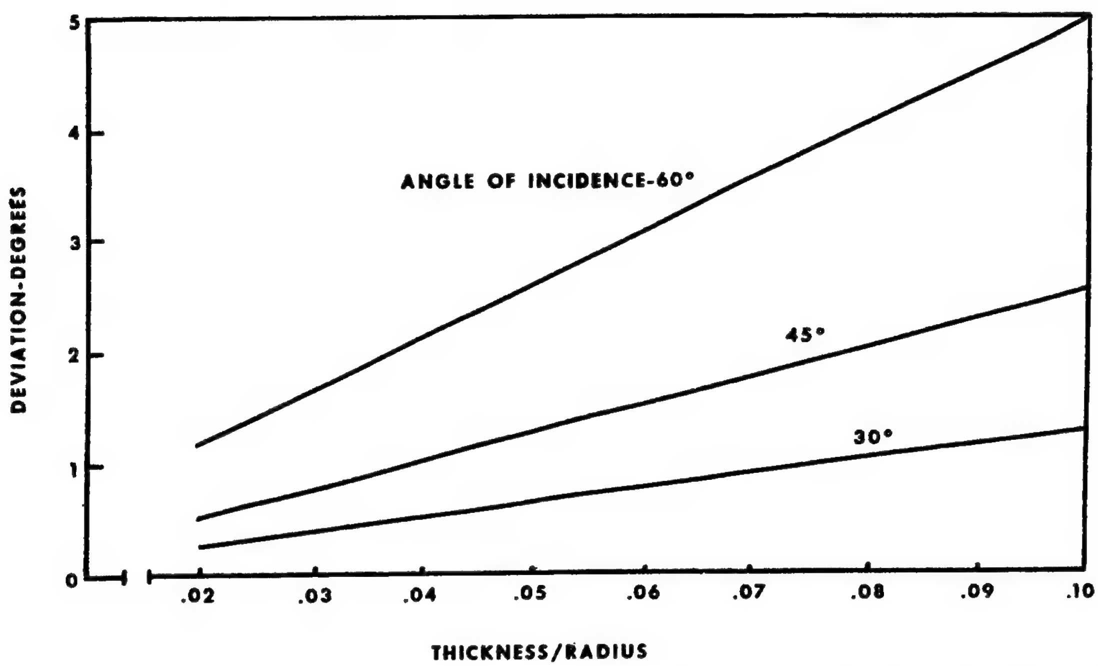

Figure 5. Effects of thickness/curvature ratio on optical deviation at three angles of incidence (from Holloway, 1970).

higher quality of transparency is required, identified as Type II. For the critical gunsight area the applicable document (Mil-G-5485C, 23 April 1971), specifies the maximum allowable optical deviation as "31.5 seconds of arc (60 seconds wedge angle)." This deviation is measured at 0 angle of incidence, not the installed angle. The specification also calls for flat glass with a minimum radius of curvature of 500 ft. Some newer aircraft, however, use a curved windshield in combination with reflector-type gunsights.

When a reflector-type gunsight or other heads-up display is used in combination with a curved windshield, there are problems in compatibility of the images being superimposed. This occurs because the angle of incidence for seeing through a curved windshield is slightly different for the two eyes, causing the condition called binocular deviation. The image from the heads-up display is collimated and reflected off a flat window, and has zero binocular deviation. Hence the eyes cannot fuse the two pictures and double images are the result. This problem has been described and studied by Fisher (1973), who has worked out what appears to be an acceptable solution using optical compensation in the heads-up display.

7. VISUAL PERFORMANCE OF PILOTS AS AFFECTED BY WINDSHIELD DESIGN

Since the beginnings of aviation, high importance has been assigned to pilot visual capability. Pilots are required to meet high standards of visual acuity, color vision, muscle balance, and absence of visual defects in both eyes. The basis for such requirements is the high premium that the pilot's duties place on visual information imputs from both inside and outside the aircraft. Because of a general trend in aviation toward increased reliance on radar, radio, and instrument aids, the needs for outside vision have been reduced for some piloting tasks, such as collision avoidance. On the other hand, the higher cruise and landing speeds have increased the distances at which visual information must be picked up in time to respond to it.

Requirements for external vision are least critical in passenger, cargo, and large bomber aircraft under noncombat conditions. Even in these, however, the pilot is still dependent on good external vision for performing many tasks. During taxi he must be able to see hand signals of ground personnel, and lights, markings, obstructions, and pavement conditions, along the taxi way. During take-off he must be able to see and interpret runway lights, runway signs, runway markings and obstructions or other hazardous conditions. During approach and landing the pilot also must be able to see lights, signs, runway markings and obstructions. But the most critical visual task probably is judging height above the runway during flare-out before touchdown. Enroute the visual requirements for collision avoidance have been somewhat reduced by present day ground control of air traffic. But, in clear weather the pilot is still required to see and avoid other aircraft.

There are additional demands on pilot vision in combat type aircraft, depending on the aircraft type and military mission. During aerial refueling vision is critical for the pilot of the receiver aircraft to hold the proper position below and behind the tanker. This task requires good vision in the forward and upward direction. Formation flying, in a similar way, requires good vision to either side in the forward direction. Flight at low altitude requires good vision forward and downward over the nose. Fighter aircraft require good vision for sighting and attacking aerial targets.

Fighter/attack aircraft, in addition, require good vision for sighting and attacking ground targets. Most fighter aircraft have reflector-type gunsights, which place special demands on windshield optics, as discussed earlier.

Under wartime combat conditions the visual capability of pilots becomes even more critical, particularly in fighter and fighter/attack aircraft. In spite of modern radar and other substitutes for direct vision, much of the actual detection and attack of aerial and ground targets during daytime is carried out by direct vision. Combat effectiveness and survival depend very much on visual detection range, visual target identification, and visual sighting accuracy with reflector-type gunsights.

What are the particular visual functions that are required in order for the pilot to perform the types of tasks described above? How much degradation of these visual functions by windshield optics can be considered acceptable? Or more to the point, what are the appropriate tradeoffs between pilot vision through the windshield and aerodynamic penalties to the airframe shape? These are difficult questions, and the answers must currently be based largely upon analysis and judgement rather than research data. An attempt was made to find research data that might help answer these important questions, but this search was largely futile.

The visual function most important for performing critical pilot tasks is visual acuity in a general sense. This includes ability to detect small targets (minimum perceptible acuity), ability to resolve detail (minimum separable acuity), ability to judge small displacement of lines (vernier acuity) and ability to see detail in moving targets (dynamic acuity) (see Grether and Baker, 1972).

The other important visual function is depth perception, also in a broad sense. Depth perception based upon binocular disparity of the images in the two eyes is important only during ground operations, formation flying, and aerial refueling. Otherwise, most of the depth or distance judgements are made at distances of 1,000 ft or more, where binocular disparity is ineffective. More important distance or depth cues are object size, texture, linear perspective (such as convergence of parallel lines) and relative motion. All of these, of course, depend to some extent on visual acuity. Very detrimental to depth perception are optical deviation and distortion, because of their effects on linear perspective.

Of obvious importance in the performance of pilot tasks is the appearance of visual targets in their true direction and their true form as seen from the pilot's eye position. In landing, for example, the shape and size of the visual image formed by the runway are vital clues to the pilot as to his position relative to the proper slope and distance from the point of touchdown. From the pilot's position on the glide slope the runway appears as a trapezoid of a particular shape. Displacements above or below the proper glide slope will cause the trapezoidal image to be elongated or flattened vertically. Displacements to the right or left will cause the shape to be distorted horizontally. Also, the pilot judges where his glide path will terminate by the point on the ground (hopefully near the runway threshold) which is stationary in his windshield. Other ground objects move radially from this point relative to the windshield. For the pilot to use these cues effectively requires good visual acuity, minimum deviation and distortion, and minimum interference from windshield haze and reflected false images. But what are the minimum levels of these that are tolerable and acceptable? Human factors research data that can be used to set tolerance levels for windshield optical degradation of visual functions are indeed scarce. Apparently the need for maximum visual capability has been taken for granted and research has not been considered necessary.

Pilot vision is often degraded by common environmental conditions, such as darkness, haze, fog, clouds, rain, snow, and glare. Vast amounts of aviation research and development have been required to overcome these obstacles to aviation, and to make it possible to fly under almost all weather conditions. Even so, it is generally accepted that the hazards of flight are increased, and combat effectiveness is decreased, when environmental conditions reduce the range and clarity of pilot vision. Handicaps to vision are common contributory factors in aircraft accidents, although the primary cause is usually classified as pilot error.

A report by Rayman (1972) shows that pilots who have been given waivers for failure to meet visual standards can cause accidents. His study lists 153 accidents in which pilots and navigators, with waivers for visual deficiencies, were involved. Of these waivers, 143 were for hyperopia or myopia, which are correctable by wearing glasses. In nine of the hyperopia and six of the myopia cases it was judged that the waivered condition contributed to the accident. In most of these accidents the pilots were not wearing their glasses, and therefore were flying with reduced visual acuity.

The effect of windshield transmission loss on visual acuity can be estimated from human visual acuity data, such as shown in Fig. 6 (from Blackwell, 1946). Also shown in Fig. 6 is the reduction in visual sighting range which results from the reduced acuity at the lower luminance levels. This curve shows that at daytime background luminance levels, 10 milli-Lamberts and above, the luminance level has very little effect on visual acuity and visual sighting range. As luminance is reduced to nighttime levels, however, visual acuity falls off quite rapidly. Thus light transmission loss has little effect on acuity during daytime, but is quite harmful at night. The ratio of transmission loss to acuity loss is about 10 to 3 at night. That is, if a windshield transmits only 10% of the incident light, this will cause the threshold visual angle to be increased by a factor of about 3.

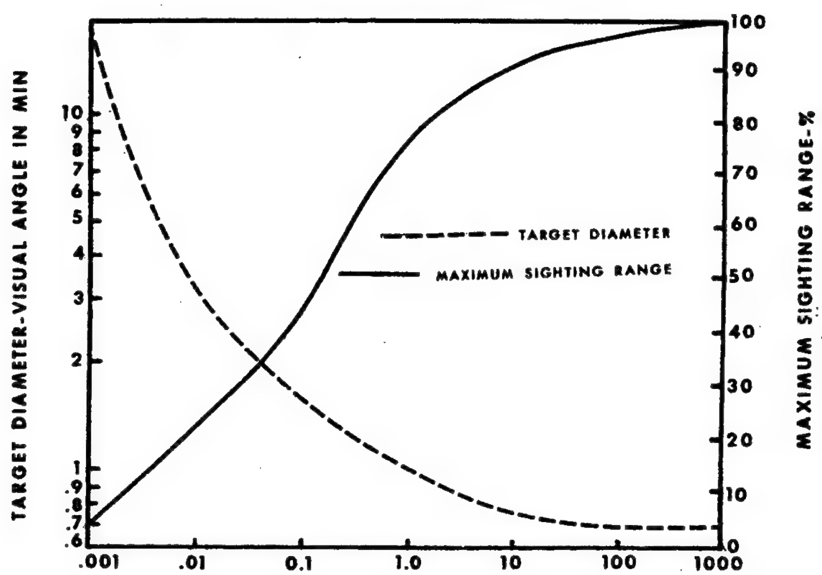

Figure 6. Effect of luminance level on minimum perceptible visual acuity and maximum sighting range (from Blackwell, 1946).

A windshield transmission factor as low as 10% is rather extreme, and probably greater than would be found in any existing military aircraft. Rather high transmission loss is anticipated, however, in the windshield of the B-1 aircraft, as shown by data from Mahaffey (1973). Windshield transmission will be approximately 40% for the horizontal sighting line, and 20% for downward vision over the nose. During development of the US Supersonic Transport by the Boeing Company, very low windshield transmission values were expected. A study by Larry (1966) predicted transmission values as low as 8.8% for the lower and 15% in the upper sections of the windshield in the nose up condition. Larry also reported a related flight test program in which these and higher transmission factors were evaluated in B-727 aircraft. Using a Cooper-Harper (1968) type scale the pilots rated the adequacy of vision for a variety of flight conditions. An overall summary of the pilot's ratings is shown in Table 2. Ratings of 4 and higher on the 9-point scale were considered unsatisfactory (U in Table 2). The data in the table include daytime, dusk, and night conditions, and takeoff, cruise and landing phases of flight. Ratings of unsatisfactory occurred much more frequently for the dusk and night than for the daytime conditions. Most of the unsatisfactory ratings were at the level of 4, although there were a few as high as 6 and 7.

TABLE 2. FLIGHT CREW RATINGS OF THE EFFECTS OF LIGHT LOSS CAUSED BY REDUCED WINDSHIELD TRANSMISSION (Larry, 1966).

Rating Basis	Transmission Range			
	8.8–15%		12–21.7%	
	Ratings		Ratings	
	S	U	S	U
Total visual adequacy and safety	51	11	32	5
Estimation of visual range	43	13	34	5
Estimation of apparent contrast	40	12	30	8
Detectability of objects important to safe flight operations	51	22	45	19

It appears from the pilot ratings obtained in Larry's study that windshield transmission factors in the range from 10 to 20% caused a considerable reduction in visual capability. This reduction showed up considerably more in the dusk and nighttime ratings, as would be predicted from the relation between visual acuity and luminance shown in Fig. 6.

A somewhat similar flight test was carried out in the Air Force by Mohr et al. (1973), in an evaluation of pilot acceptability of a proposed atomic flash protection method. This study was carried out in a T-38 aircraft. Windshield transmission was reduced to approximately 10%. In addition the visual area was reduced to a window 6 inches high and 8 inches wide placed about 10 inches from the pilot's eyes. Cooper-Harper-type ratings on a 9-point scale were obtained from 7 pilots. Each pilot made two night flights. On the first flight his vision was restricted only by the window. On the second flight a filter was placed in the window which, added to the T-38 windshield loss, reduced the total light transmission to about 10%. Ratings were obtained for different visual tasks required during taxi, takeoff, and landing.

The pilot ratings from the study by Mohr et al. are summarized in Table 3, in terms of overall average and maximum ratings on a 9-point scale. As the scale was set up, normal vision in the T-38 aircraft was assigned a rating value of one. This study did not obtain ratings of reduced windshield transmission independent of the area restriction. It appears that the reduced transmission had somewhat less effect on the pilot's ratings than did the restriction in visual area. From the verbal comments of the pilots, however, it was clear that some visual capabilities were significantly impaired by the reduced light transmission. For example, anti-collision lights of other aircraft were first detected at considerably shortened distances. Also, the distance was reduced at which the colors of VASI approach lights could be correctly interpreted. One pilot almost failed to notice the lights of another aircraft ahead of him while taxiing.

TABLE 3. PILOT RATINGS ON 9-POINT SCALE OF ABILITY OF TAXI, TAKEOFF AND LAND WITH RESTRICTIONS IN WINDSHIELD AREA AND LIGHT TRANSMISSION (Mohr et al., 1973).

Flight Phase	Visual restriction by window only		Visual restriction by window plus 10% transmission	
	Average ratings	Maximum ratings	Average ratings	Maximum ratings
Taxi	2.2	5	2.5	5
Takeoff	2.3	5	2.5	5
Approach & landing	2.5	5	2.8	6

Acceptability of tinted windshields in both aircraft and automobiles has been studied in relation to transmission loss. Allen (1970) has reviewed the data for and against tinted windshields in automobiles, and concluded that tinting is undesirable for driving at night because of the reduction in visual acuity. Allen quotes 70% as the minimum light transmission value recommended by the Society of Automotive Engineers for automobile windshields. Crosley (1968) has studied the desirability of tinted windshields for use in Army aircraft. He has likewise recommended that tinted windshields not be used, because of the reduction in visual efficiency at night. Clark (1971) in Australia analyzed an aircraft accident in which he believes that the light transmission of the tinted windshield was approximately 61%. During a night flight the pilot failed to see a mountain peak in time to avoid it.

A study by Schacter and Chapanis (1945) showed the effect of some windshield factors on depth perception, as measured by the Howard-Dolman test. Their data are summarized in Fig. 7, which shows how the depth perception threshold was degraded as the angle of incidence was increased. Also shown is the effect of the quality of the window material. Another study by Loper and Stout (1969) also used the Howard-Dolman test, and measured the effects of window distortion on test scores. Their data are shown in Fig. 8. The Howard-Dolman test measures primarily one aspect of depth perception, namely, binocular disparity. Since this depth cue is only effective at rather short range, it probably has minimal importance in aviation. Most likely depth cues, such as relative size, linear perspective, and relative motion would also be degraded by distortion, but no relevant research data were uncovered in this review.

An important pilot visual capability is the visual range at which targets, such as other aircraft,

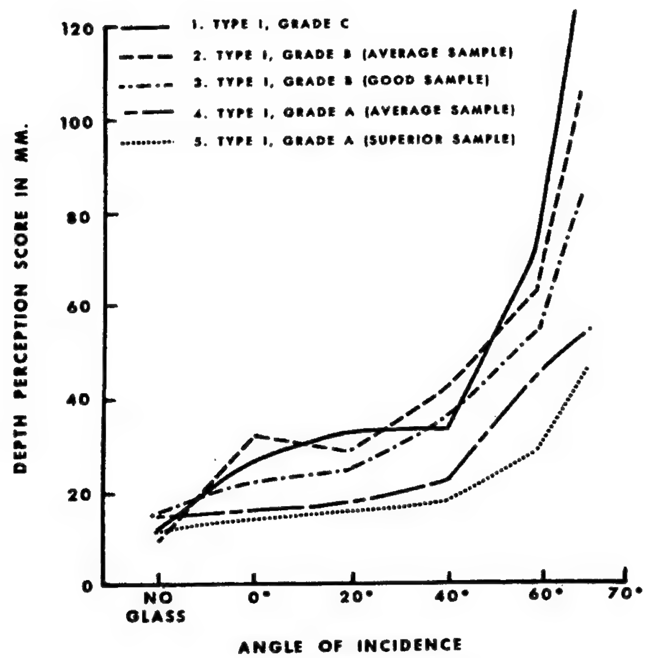

Figure 7. Effect of angle of incidence and windshield quality on binocular depth perception (from Schachter and Chapanis, 1945).

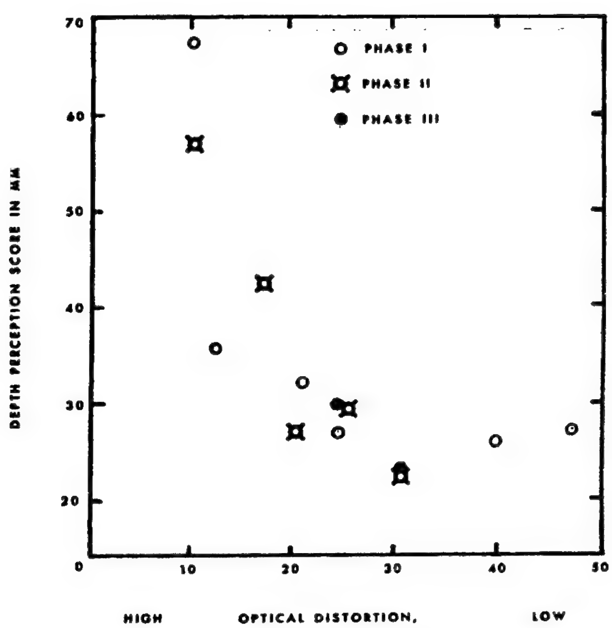

Figure 8. Effect of optical distortion on binocular depth perception (from Loper and Stout, 1969).

can be detected. Any factors that degrade visual acuity, primarily haze and transmission loss, will reduce the range at which targets can be detected and identified. A study by Luczak (1943) showed how the quality of the transparent material and the angle of incidence affect visual detection range. His major results are presented in Fig. 9. His results, like those of Schacter and Chapanis (1945) emphasize the importance of quality and surface condition of the transparent material.

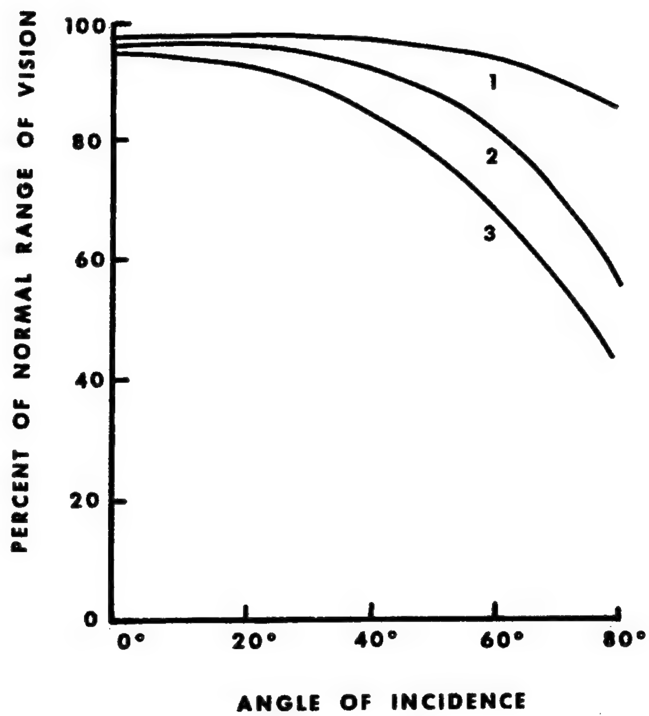

Figure 9. Effect of angle on incidence and windshield quality on visual target detection range: (1) plate glass; (2) clean plastic; (3) dirty plastic (from Lucazk, 1943).

8. PILOT ATTITUDES CONCERNING WINDSHIELD OF F-111 AIRCRAFT

In this survey no attempt was made to gather representative pilot attitudes concerning adequacy of windshields in different aircraft types. However, the F-111 windshield represents an extreme departure from the former use of flat panels and 60° maximum angle of incidence. For this reason a small sampling was made of observations of F-111 pilots concerning visibility in that aircraft.

The F-111 aircraft has side by side seating, with the pilot on the left and the observer on the right. The forward windshield consists of two curved panels on either side of a common structural support at the midline. This windshield divider slopes up to a canopy bow somewhat forward of the eye positions of the two crew members. For vision directly ahead the angle of incidence is about

69°, and the radius of curvature ranges from 18 in. at the front to 31 in. at the rear part of each panel. The eye position of the pilot is considerably to the left and above the center of curvature.

Seven F-111 pilots were interviewed during a visit to the Tactical Fighter Weapons Center, USAF Tactical Air Command, Nellis AFB, Nevada. Arrangements for the visit were made through Maj. W. P. Leggett (TFWC/TEM), who was the primary point of contact at the Tactical Fighter Weapons Center. Although the sample of pilots was small and not necessarily representative of all F-111 pilots, their observations do indicate a number of rather serious deficiencies that appear to be inherent in the windshield design. A personal inspection of the crew station of an F-111 in a hangar helped in providing an understanding of the pilots' complaints. The major deficiencies described by the pilots were the following:

A. BLIND AREAS FROM OBSTRUCTIONS TO VISION.

The structure dividing the two windshield panels, and the overhead canopy bow just forward of the two crew members, are considerably wider than the distance between the two eyes. Thus blind areas are created which cannot be overcome with binocular vision (see Wulfeck et al. 1958). These blind areas occur at both sides of each crew member, as well as overhead and forward. The pilots found these obstructions to be at such locations that they handicapped vision needed for formation flying and aerial refueling operations. There were also visual obstructions that were quite unrelated to windshield design. In particular, the pilots complained quite strongly about the visibility obstructions caused by side by side, as opposed to tandem, seating. Also they found the vision over the side and to the rear much more restricted in the F-111 than in older fighter aircraft.

B. OPTICAL DISTORTION.

All of the pilots seemed to have experienced some optical distortion. It was reported that some windshield panels with particularly bad distortion had been replaced, thereby somewhat alleviating the problem. Distortion was reported to be greatest at the edges of the windshield and minimal for central forward vision. Some pilots reported uncertainty about the height above the runway during landing, because of windshield distortion. They indicated, however, that this was not a serious handicap in the F-111, since landings were typically conducted without flare-out before touchdown. At least one pilot reported that during low altitude flight, he depended on the radar altimeter rather than vision for information about height above the terrain. He did this, he said, because windshield distortion made visual judgments of height above the ground unreliable at very low altitudes.

C. MULTIPLE IMAGES.

Several of the pilots had experienced multiple images at night, and found them to be a major distraction. One pilot, in particular, reported the appearance of duplicated landing light images to the left of the true position. In the F-111 the windshield curves downward to the left of the pilot's eye position. This accounts for the duplicated images being to the left.

D. COMPATIBILITY OF WINDSHIELD AND REFLECTOR GUNSIGHT.

One pilot reported difficulty in using the reflector-type gunsight, which combines the gunsight picture, reflected off a flat glass plate with the forward view seen through the curved windshield. The exact nature of the difficulty was not clear, but could be due to binocular deviation (see section 6) caused by the curved windshield. Other pilots said that they rarely used the reflector sight, and therefore had no comments to offer concerning problems associated with it.

E. COMPARISON OF WINDSHIELD OF F-111 AND OTHER AIRCRAFT.

The pilots who were interviewed had flown a variety of older aircraft. They were asked how they liked the windshields of other aircraft, by comparison with the F-111. The general answer was that they much preferred the windshields of the older aircraft. Specifically mentioned were better forward visibility, fewer and narrower blind areas caused by structural members, and better visibility over the side and to the rear.

9. ACCEPTANCE STANDARDS FOR OPTICAL PARAMETERS OF AIRCRAFT WINDSHIELDS

While the data on pilot visual performance and pilot ratings verify the need for vision to be as good as possible, they do not provide a suitable basis for the setting of optical standards for aircraft windshields. In actual practice, the standards which exist are rather arbitrary, and are based to a considerable extent on what the industrial production technology can provide.

Recommended standards for haze and light transmission were published by Glover (1955), based upon laboratory tests he conducted. The values he arrived at are shown in Table 4, taken from his report. Apparently the values in that table are for measurements made at zero angle of incidence. The recommended values for transmission increase with incidence angle in order to compensate for reduced transmission as the angle of incidence is increased. At the installed angles the recommended values in the highly desirable and acceptable categories would be about 66 and 60%, respectively. Unfortunately Glover does not give the data or analyses from which his values were derived.

TABLE 4. LIGHT TRANSMISSION AND HAZE VALUES (From Glover, 1955).

		WINDSHIELDS				CANOPIES	VISORS
		INCIDENCE ANGLE					
		55°	60°	65°	70°		
HIGHLY DESIRABLE VALUES	Transmission	71%	74%	83%	99%	89%	90%
	Haze	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
ACCEPTABLE IF OTHER FACTORS TAKE PRECEDENCE	Transmission	66%	69%	78%	93%	83%	86%
	Haze	1%	1%	1%	1%	1%	1%
MINIMUM VALUE	Transmission	64%	67%	75%	89%	77%	79%
MAXIMUM VALUE	Haze	2%	2%	2%	2%	2%	2%

Standards for the most important optical parameters have been provided for many years in US military specifications. A summary of optical requirements for windshields of US military aircraft, as provided in several specifications, is given in Table 5. Transparencies are classified into Type I, bullet resistant, general purpose; and Type II, bullet resistant for use with reflector-type gunsights. Within each Type there is a further breakdown into Grades A, general purpose, and B, high light transmission.

Note that the standards in Table 5, in most instances, are given for zero angle of incidence, rather than the installed angle. To determine what these values would be at the installed angle, the multiplication factors given in Figures 2 and 3 can be applied. It would be more realistic, however, to provide standards for the installed angle. It is understood that the testing of windshields for distortion, by aircraft manufacturers, is normally performed at the installed angle.

TABLE 5. OPTICAL ACCEPTANCE STANDARDS FOR TRANSPARENCIES OF U.S. MILITARY AIRCRAFT.

Optical Parameter	Standards	Source
Angle of Incidence	60° maximum throughout windshield	AFSC–DH–2–1 DN 3A1, 1969
	60° maximum in any part used for approach and landing	MIL–W 81752 (AS) 1970
	60° maximum at horizontal vision line	MIL–STD–850B 1970
Radius of Curvature Type II, A&B	Flat, minimum radius 500 ft	MIL–G–5485C, 1971
Deviation at 0° angle of incidence Type I Type II	 3 min. maximum 31.5 sec. maximum	MIL–G–5485C
Deviation at installed angle, in gunsight area	±1.8 min. maximum	AFSC–DH–2–1 DN–3A1, 1969
Transmission at 0° angle of incidence Grade A	Range from 81% for ½" to 71.6% for 3" thickness	MIL–G–5485C
Grade B	Range from 85% for ½" to 78% for 3" thickness	MIL–G–5485C
Distortion	To be specified by procuring agency	MIL–G–5485C & MIL–G–25667B
	Deviation change per inch of surface at installed angle, for: Optically flat 1.0 min/in Flat 2.5 min/in Single Curved 4.0 min/in Compound 5.0 min/in	AFSC–DH–2–1 1969
Haze, at 0° angle of incidence	1% up to ⅜" thickness 1.5% for ⅜" to 1¼" thickness	MIL–G–25667B, 1970

Corney in Great Britain has given considerable study to optical requirements for aircraft transparencies, and has offered tentative standards for use at the installed angles. Table 6 is taken from a recent report by Corney (1973). He offers standards for four categories of transparency, which are listed at the top of the table. At the bottom of the table are the proposed uses for the four categories. Considering that the values proposed by Corney are for the installed rather than zero angle of incidence, his values are in fair agreement with those given in Table 5, taken from US military specifications.

TABLE 6. ACCEPTABLE VALUES OF THE PARAMETERS ASSOCIATED WITH VISION THROUGH OPTICAL TRANSPARENCIES (Corney, 1973).

Parameter	Category I	Category II	Category III	Category IV
Optical Resolution value not to exceed	1 minute	1 minute	2 minutes	—
Haze value not to exceed	2.5%	2.5%	2.5%	—
Optcal Transmission not less than	55%	55%	55%	50%
Optical Deviation	<5 minutes tolerance from and agreed value	<15 minutes	<20 minutes	—
Distortion		Change in slope not greater than 1 in 20	Change in slope not greater than 1 in 20	Change in slope not greater than 1 in 5
Binocular Deviation value not to exceed	10 minutes	10 minutes	10 minutes	—
Double Imaging	←——Standards	to be decided	——→	
Scratches and Inclusions, etc.	←——Provisional	Standards under	discussion	
Type of transparency (or area thereof)	Forward facing windscreen of the highest quality—suitable for weapon aiming	Forward facing and side panels for reconnaissance and search: forward panels for non-combat aircraft	Side panels for non-combat aircraft—canopies	Cabin windows

10. MEASUREMENT TECHNIQUES FOR TESTING WINDSHIELDS TO DETERMINE COMPLIANCE WITH OPTICAL STANDARDS

Most of the optical parameters discussed in this report can be measured by straightforward applications of geometry and physical optics. Such methods are described in most of the applicable military specifications. They can also be found in reports by Corney and Shaw (1971) and Corney (1973). Only one of the parameters listed in Tables 5 and 6, namely distortion, presents special problems concerning methods and units of measurement.

Most methods of measuring distortion involve a camera located at a position representing the pilot's eye position, the transparency, and a test grid at a suitable distance beyond the transparency. Beyond this basic setup, there is considerable variation in the methods that have been used. A fairly standard method uses double exposure, with and without the transparency in place. Any distortion will then be revealed by splits in the grid lines, and by bending of some of the lines. Several measurements are possible, such as the number of places where splits occur, the maximum width of the splits, and the maximum slope changes in grid lines.

Several variations of this basic technique have been proposed and used. For the Navy, Brown, Crumley, and Alsker (1954), Crumley, Atkinson and Fletcher (1954), and Lazo (1954) have used and recommended a technique involving a single photographic exposure with a two-hole mask over the camera lens. The windshield was placed at the appropriate place and installed angle with reference to the pilot's eye position. The acceptance criterion, or standard, was set in terms of the number of line splits that appeared in the photograph. In evaluating this technique, Smith (1958), concluded that the results were unreliable. The number of line splits varied too much with the test setup, the type of lens, the type of mask, the film processing method, and the judgement of the film reader in counting splits.

At the McDonnell Aircraft Company, St. Louis, Cocagne (1969) used a triple-exposure method. With the transparency located at the proper distance and installed angle relative to the camera, an exposure is made through the center of the windshield panel. Two more exposures are made with the panel moved upward, and then downward, two inches from the center position. Then another triple exposure is made through the center and two inches to the right and left of center of the panel. A maximum grid line growth of 0.014 inch, as measured on the triple exposure photograph, was taken as a rejection standard. Such growth was reported as indicating a maximum deviation change of 3.74 min.

Any of these grid photography methods involve considerable labor in measuring line splits, line growths, or line slope changes if the methods are to give accurate quantitative values. There seems to be no agreement as to which particular method of photography or analysis of the photograph is most satisfactory. Very often a mere visual examination of the photograph, or look at a grid through the transparency, will provide an experienced inspector with an adequate basis for accepting or rejecting a panel. Although such visual inspection is said to give good agreement with objective optical tests, it is too subjective to serve for acceptance testing.

11. EFFECTS OF WINDSHIELD GEOMETRY ON AIRCRAFT COST AND AERODYNAMIC EFFICIENCY

As mentioned in the introduction to this report the requirement for good pilot vision is in direct conflict with the need to streamline the aircraft to minimize aerodynamic drag. This conflict is particularly serious at supersonic speeds. As discussed earlier in Section 4 and shown in Table 1, recent USAF aircraft designed for high speeds have used curved windshields with angles of incidence exceeding 60°. In addition to having undesirable effects on pilot visual capabilities, as shown in this report, such windshields have probably added considerably to the aircraft cost. In this section some examination is made of tradeoffs among aerodynamic drag, windshield cost, and pilot vision. It must be pointed out, however, that aerodynamic and cost factors are outside both the basic purpose of this review and the technical competence of the author.

Among the reports found in this literature survey was a paper by Rubin (1968) that attempted to optimize windshield angle for high speed aircraft. Rubin pointed out that as the angle of incidence is increased the windshield cost for grinding and polishing must be increased in order to maintain constant values of deviation and distortion. Using this logic he generated an arbitrary curve of cost which increased very rapidly as incidence angle exceeded 60°. He also presented a curve of light

transmission like that in Fig. 3, and a curve of aerodynamic drag which showed very little drag reduction for incidence angles above 60°. Rubin further combined the three parameters, cost (C), light transmission (T), and drag (D) into a single figure of merit, namely T/D+C. Using his curves for C, T, and D, he showed that the combined fraction (T/D+C) reached a maximum at an angle of incidence of about 58°. Even when drag was given a weighting of 10 in the fraction (T/10D+C) the figure of merit reached a peak at an angle of incidence of about 60°.

While Rubin admitted that his curves of cost and drag were arbitrary, his general logic appears to be defensible. Certainly, to maintain equal values of deviation and distortion, windshield cost must go up as the angle of incidence is increased. Also, for comparable optical quality, curved transparencies are considerably more expensive than are flat panels. Cost data are beyond the scope of this report, and reliable cost comparisons for different aircraft windshields may be difficult to obtain. It is understood, however, that the windshield of the F-111 is a rather high cost item and that the replacement cost for a single panel has been in the range from $16,000 to $20,000. A large part of the high cost results from a very high rejection rate in the acceptance testing of the windshield panels, and from the manufacturing problems encountered in attempting to attain the optical quality required.

A major factor affecting cost is the size of the panels making up the windshield. As the area of the transparency increases, larger machines are required for forming and other manufacturing operations. Also, the problems of maintaining acceptable optical quality become magnified. Thus the costs increase in much more than a linear manner as the area becomes larger. An apparently small increase in angle of incidence, such as going from 60° to 65°, will cause a considerable increase in windshield area, and thereby a relatively high increase in overall cost.

While it is obviously important to minimize drag in a high speed aircraft, it seems worthwhile to examine what the drag cost would be for providing windshield geometry that would give improved vision for the pilot. Some data on the tradeoffs between drag and windshield geometry are available in a study from General Dynamics (1968) with reference to the windshield of the F-111B. After evaluating the aircraft for operation from aircraft carriers, the Navy specified a number of design improvements that would be required. Among the deficiences identified by the Navy was that the pilot visibility from the F-111B was unacceptable for landing on carriers. The Navy, therefore, requested a "Cockpit module reconfiguration to provide about 3.7 degree improvement of (down) vision inclusive of a windshield angle change necessary to improve light transmission."

One of the major changes called for in the reconfiguration requested by the Navy was a change in windshield slope from 21.5° to 30° (i.e., from angle of incidence of 68.5° to 60°). The General Dynamics study report (1968), pages 93 & 94) presents their findings concerning the effects of such a change on aircraft drag. A summary of the resulting data, taken from that report, is shown in Fig. 10. At the top of the figure are side views of the windshield configurations which were studied. Presented in Fig. 10 are drag rise data at 0.75, 0.90, and 1.2 Mach for going from 21.5° to 30° windshield slope. For a curved windshield the drag increases caused by this slope change are shown to be 0 $\triangle C_D$ at Mach 0.75; 0.0004 $\triangle C_D$ at Mach 0.90, and around 0.001 to 0.0015 $\triangle C_D$ at Mach 1.2 For a windshield made up of flat panels (shaded curve in Fig. 10) the drag rise is considerably higher.

The overall drag, C_D, of the F-111 at supersonic speed is approximately 0.04. Based on this

value, the drag increase, caused by a change to a 30° windshield (60° angle of incidence) would be approximately 3% at supersonic speeds. At subsonic speeds the percentage drag increase would be considerably less. For a change from the present F-111 windshield to a flat configuration and a 30° slope it appears that the drag rise at Mach 1.2 would be about 8% of overall drag.

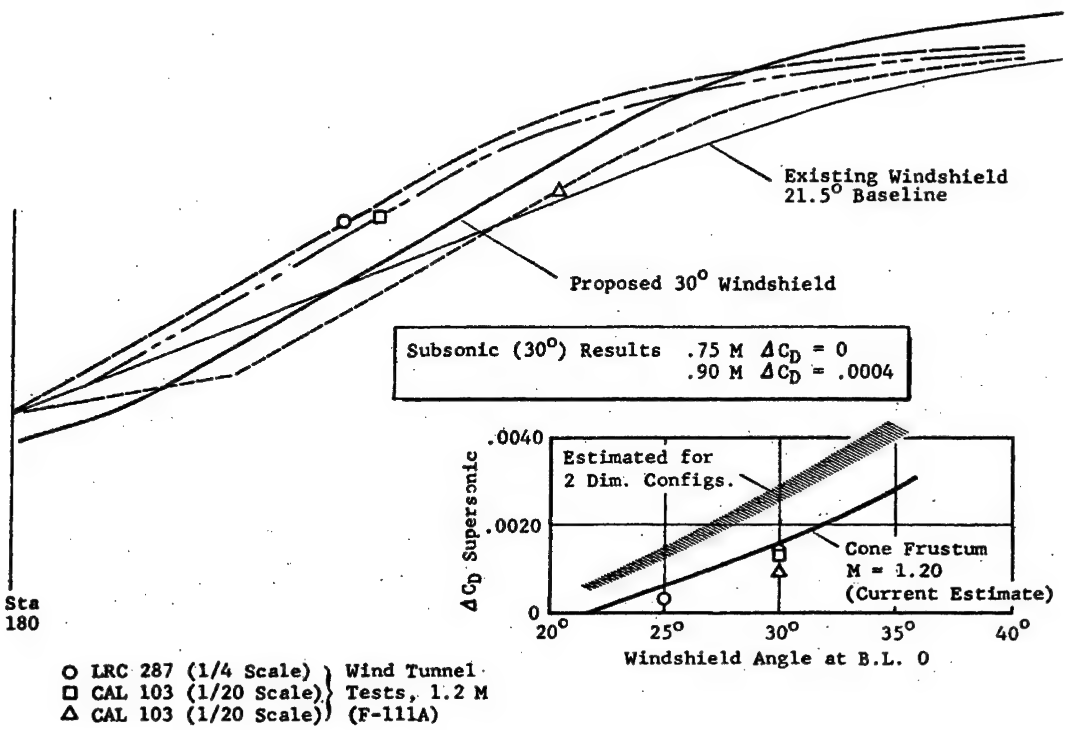

Figure 10. Effect of windshield geometry on aerodynamic drag for F-111B aircraft (from General Dynamics, 1967).

A reconfigured F-111B aircraft, providing the improved visibility, was never built. There was, therefore, no chance to follow up and verify either the predicted increase in drag or the improvements in visibility for the pilot. It would seem, however, that an overall drag rise that is near zero at subsonic speeds, and only 3% at supersonic speeds, would not have been too high a price to pay for acceptable visibility for the pilot. Although quite beyond the scope of this report, it would seem worthwhile to conduct a cost/effectiveness study to evaluate the effects of windshield geometry on aerodynamic drag, aircraft cost, combat effectiveness, and flight safety.

12. DISCUSSION

This literature review shows how the slope and curvature of aircraft windshields produce optical effects that have an important influence on the quality of pilot vision in the forward direction. Un-

fortunately there is a basic incompatibility between the windshield geometry that is required for good pilot visibility and that which causes minimum drag at high speed. The optical effects that degrade pilot vision are governed by physical laws, which are just as fundamental and invariant as are the laws of aerodynamics with which they come in conflict. Aircraft designers and their customers, as a consequence, are faced with a difficult choice among alternative windshield designs. Designs that maximize aerodynamic efficiency cannot avoid penalties to pilot vision through the types of optical degradation discussed in this report. It is hoped, however, that this review will be of assistance to aircraft designers and their customers in finding acceptable compromises in the choice between pilot vision and aerodynamic efficiency.

For a single-place or tandem aircraft there are two common types of windshield design: (1) A flat panel sloping up to a canopy bow just ahead of the pilot, with curved panels at each side; and (2) A one-piece curved wrap-around panel. There are advantages and disadvantages to each design.

The first and older design, used on such aircraft as the F-4 and F-14, both designed to basic Navy requirements, provides flat glass in the most critical area. This is the area for seeing directly ahead, for visual sighting using a reflector-type gunsight, and for viewing of a heads-up display of flight data. The use of flat glass avoids the optical problems inherent to curvature as discussed earlier in this report. On the other hand, with this type of windshield there is obstruction of vision from the framing that joins the flat front panels to the curved side panels.

The second and newer type of windshield design, used on such aircraft as the T-38, F-5, and F-15, is more efficient aerodynamically. It also avoids the visual obstructions of the framing around a flat front panel, and thus provides a clear visual field back to the canopy bow. The use of curvature, however, results in increased deviation and distortion effects, and introduces binocular deviation with consequent complications in the use of a reflector-type gunsight or heads-up display. Optical degradation of pilot vision with this type of windshield will be minimized by using an angle of incidence of 60° or less, using single curvature, and placing the pilot's normal eye position at the center of the curvature in the horizontal plane. It is understood that this type of one-piece wrap-around windshield is considerably more expensive than the older three-piece design. The cost is higher for initial development and throughout the life of the aircraft.

For side by side cockpits the windshields are normally made up of a front panel before each pilot, plus additional panels at the sides. The front panels are either curved or flat, are joined at the midline, and normally slope both upward and to the side. Such an arrangement, with either flat or curved panels, provides good forward vision if the angles of incidence are relatively low in both the vertical and horizontal planes. At extreme angles of incidence combined with curvature, such as in the F-111 and B-1, pilot vision is considerably degraded by deviation, distortion, low transmission, and multiple images. The deviation and multiple image problems are magnified by having the pilot's eye position considerably displaced from the center of the curvature in the horizontal plane. The optical degradation would be somewhat reduced by use of a "double bubble" arrangement in which the eye position for each pilot is at the center of the arc, in the horizontal plane, for his windshield panel. But such an arrangement would probably be less efficient aerodynamically, and might create cross-cockpit visual problems. Whether the windshields are curved or flat, the quality of pilot vision is rapidly degraded as angles of incidence are increased above about 60°.

Presumably because of the need for making visually guided landings on aircraft carriers, the Navy has maintained stricter optical criteria for aircraft windshields than has the Air Force. The Navy has continued to require flat panels for forward vision and angles of incidence of 60° or less. This difference in design requirements is reflected in the data shown in Table 1. It appears also that the Air Force has been somewhat more lenient than the Navy in permitting deviations from existing windshield design standards as published in the current design specifications (See Table 5).

13. SOME SUGGESTIONS FOR FURTHER STUDY

As a result of conducting this review the author has a number of suggestions about further efforts that would benefit aircraft designers and their customers in making design decisions for future aircraft. First, it would be very helpful to have a mathematical model to aid in making the tradeoffs among aerodynamic efficiency, cost, and pilot visual performance as they relate to windshield configuration. For such a model to have much real value, more and better data are needed concerning the effects of varying degrees of visual degradation upon flight safety and combat efficiency. Analysis of existing accident data at the Air Force Inspection and Safety Center, Norton Air Force Base, would probably provide useful data on how visual degradation affects cost through accident losses. An appropriate operation analysis, based upon combat data in Vietnam, could probably provide data on how visual degradation affects combat efficiency and survival rates. A mathematical model on windshield design should also include data on windshield manufacturing and replacement costs. For this purpose cost data for current aircraft windshields would give useful estimates.

Another type of study that should help in making future windshield design decisions would be a survey of pilot opinions. Many pilots have flown a variety of aircraft with different windshield configurations. Their observations and preferences concerning windshield design would provide a valuable set of data. For example, there are many pilots who have flown both T-38s, with one-piece wrap-around windshields, and F-4s (or other aircraft) with a flat front and curved side panels. All pilots of F-111s will have had experience with windshields in other aircraft and could make helpful comparisons. Probably most pilots would have helpful observations about vision through curved and flat windshield panels. Certainly, the pilots opinions and preferences deserve consideration in choosing windshield designs.

For the optical acceptance testing of windshields there is still no agreement on the best method of measuring and quantifying distortion. If further comparisons were made among the existing methods then it would probably be possible to select one as the most discriminating, reliable, and efficient to use. Or possibly a new approach, such as laser beam scanning, would offer a better way to measure distortion.

14. SUMMARY

This report provides a review of the literature on pilot vision as affected by the geometry and optical characteristics of aircraft windshield design. Included in the report is some examination of military standards and optical testing of windshields. The major findings of the literature review are as follows:

(a) Windshield geometry, in terms of slope and curvature, that is optimum for high speed flight results in serious degradation in pilot vision in the forward direction.

(b) The optical effects of windshield geometry follow well-known laws of physical optics. Those effects which cause significant degradation of pilot visual capabilities are deviation, distortion, binocular deviation, reflections, multiple images, haze, transmission loss, and reduced resolution.

(c) For minimal degradation of pilot vision, the angle of incidence should not exceed 60° (i.e., slope not less than 30°), and the transparent panel should be flat rather than curved. Vision deteriorates rapidly as the angle of incidence exceeds 60°, and with curvature of the transparency. If curvature is used, the radius of curvature should be as large as possible, curvature should be simple rather than compound, and the pilot's eye position should be near the center of the curvature.

(d) The use of a curved windshield results in binocular deviation (i.e., unequal deviation for the two eyes). Because of this, the use of a reflector-type gunsight or heads-up display results in double images and sighting errors, unless suitable compensation is provided in the optical system of the heads-up display.

(e) The use of a curved windshield, high angle of incidence, and a pilot eye position displaced from the center of curvature produces problems of optical distortion and multiple images, which severely degrade pilot visual performance.

(f) Windshield geometry and optical quality called for in existing military standards and specifications are adequate, and if complied with, provide good pilot vision in the forward direction. Generally, however, these specifications define optical quality for 0° angle of incidence, rather than the installed angle. A revision of military specifications to provide optical standards and test methods applicable to the installed angle would be desirable.

(g) There is, currently, no agreement as to the best method for measuring distortion in the optical testing of windshields, although a variety of methods are available. Further study, and possible agreement on a standard method for measuring distortion, appears to be needed.

(h) There is, currently, no adequate method of selecting an optimum windshield design, based on considerations of aerodynamic efficiency, pilot visual performance, and cost. It is suggested that efforts be directed toward development of a mathematical model for making tradeoffs among these three parameters.

(i) As an aid in the selection of windshield configurations for future aircraft, it would be helpful to have a systematic collection of pilot opinions, based upon their experience in flying different aircraft.

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ARMSTRONG LABORATORY

DEFINITIONS OF TERMS RELATING TO AIRCRAFT WINDSCREENS, CANOPIES, AND TRANSPARENCIES (U)

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FOR THE COMMANDER

KENNETH R. BOFF, Chief
Human Engineering Division
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13. ABSTRACT (*Maximum 200 words*)

This report presents a glossary of terms relating to aircraft windscreens, canopies, and transparencies. It addresses the need to have a single reference source which provides a common vocabulary for use by designers, materials engineers, manufacturers, evaluators, maintenance personnel, and user agencies concerned with aircraft transparencies. Its intent is to facilitate and enhance communication between these disciplines by clarifying and defining terms used within the aircraft transparency industry.

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Preface

This report was prepared under work unit 7184-18-03, Transparency Effects on Visual Performance, by personnel of the Visual Display Systems Branch (AL/CFHV), Human Engineering Division, Armstrong Laboratory, Wright-Patterson Air Force Base, Ohio. Funding for this effort was provided by the Wright Laboratory's Aircrew Protection Branch (WL/FIVR).

The authors would like to express their sincere thanks and appreciation to the members of the American Society for Testing and Materials F7.08 subcommittee task force on terminology for their invaluable help in ensuring the correctness and appropriateness of the terms used in this report. Special thanks goes to Mr. Harold Merkel of Compaq Computers Inc. who initiated this effort while a member of Armstrong Laboratory.

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Introduction

This report presents a glossary of terms relating to aircraft windscreens, canopies and transparencies. The need for a report of this genre was provided by subcommittee F7.08, "Aircraft Enclosures and Transparencies," of the American Society for Testing and Materials (ASTM). Meeting twice yearly, the membership of this subcommittee is made up of individuals and organizations involved in materials development, manufacturing, design and evaluation and utilization of aircraft enclosures and transparencies. At these meetings it became increasingly clear that each of these varied disciplines had a language of its own and that terms used by people working in one discipline did not convey the same meaning to people working in the other three disciplines.

This report has been prepared to address the need identified by ASTM Subcommittee F7.08. Specifically, to develop a single reference source which provides a common vocabulary for use by designers, materials engineers, manufacturers, evaluators, maintenance, and user agencies concerned with aircraft transparencies. By clarifying terms used within the aircraft transparency industry, communication between the various disciplines would be facilitated and enhanced.

The terms selected for inclusion in this report were taken from the various reference sources listed in the bibliography. Additionally, various organizations representing the various disciplines working within the transparency industry were solicited to provide additional terms. The final list of terms were subjected to scrutiny by a task force of 18 individuals whose task was to ensure (1) that each term was correctly defined and (2) each term merited inclusion in the report.

Definitions

A

aberration – Failure of the rays from a point source to form a perfect or single point image after passing through an optical system. This manifests itself as formation of multiple images or formation of single imperfectly defined images.

abrasion shield/coating – A thin sheet of glass, plastic, or other transparent surface finishing material applied to the inside or outside face of a transparency to resist abrasion.

absorption – The amount of light that is neither reflected nor transmitted but is retained within the object.

achromatic – Lacking in hue and saturation. Achromatic colors vary only in brightness from black to white (colorless).

acrylic – Thermoplastic or thermoset material produced by a polymerization of the monomeric derivatives of acrylic acid; supplied in forms of cast sheets, rods, bars, tubes, crystals, granules, or powder; may be transparent, opaque or a variety of colors. Also known as an acrylate, a methacrylate base, or polymethyl methacrylate (PMMA).

acrylic, cross-linked – A thermoset plastic sheet of cast acrylic used to make stretched acrylic.

acrylic, stretched – A polymethyl methacrylate plastic sheet that has been heated and stretched either in two perpendicular directions (biaxial) or in all directions (multiaxial) in the plane of the sheet. This improves crack propagation and craze resistance by realigning the molecules.

acuity, visual – The smallest detail that the eye is capable of resolving at a specified distance. Expressed by visual angle in minutes of arc.

ADBIRT – Advance Design Bird Impact Resistant Transparency. See *BIRT*.

adherend – An object bonded by an adhesive.

ambient light – Light surrounding all sides (existing lighting conditions of the environment).

amorphous – Without crystalline molecular structure.

analyzer – A polarizing element that can be rotated about its axis to control the amount of transmission of incident plane polarized light, or to determine the plane of polarization of the incident light.

angle, critical (Θ_c) – The angle of incidence at which the angle of refraction is 90°for the interface of two optical media. At angles of incidence greater than Θ_c, total internal reflection occurs.

angle of deviation – The angle through which a ray of light is bent by reflection or refraction. It is expressed in minutes of arc, degrees or milliradians.

angle of incidence – The angle between the incident ray of light and a line normal to the surface of the transparency.

angle of installation – See *installed angle.*

angle of reflection – The angle between the reflected ray and a normal to the surface.

angle of refraction – The angle made by the refracted part of a light ray with a line perpendicular to the surface of the refracting medium through the point of incidence of the refracted ray.

angle of view – The angle subtended by the total field of view at the observer's eye position.

angstrom – A unit of measurement of wavelength of light equal to 10^{-8} cm. Abbreviated A.

angular deviation – The angular displacement of a light ray from its original path as it passes through a transparent material. It is expressed in units of angular measurement (degree, minutes of arc, milliradians).

angular deviation device – A device that measures the angular deviation of a collimated beam of light, in azimuth and elevation, as it passes through a transparency.

angular displacement – The angular separation of the secondary image from the primary image as measured from the design eye position of a transparency. See *multiple imaging separation.*

annealing – The controlled heating and cooling of a material according to a prescribed schedule to minimize residual stresses.

annealing schedule – The relationship between time and temperature at which a material is exposed to assure proper annealing.

anti-icing – A method of preventing or removing ice accumulation.

antireflective coating – A thin film applied to a transparency surface to reduce its reflectance.

antistatic agents – Agents which minimize static electricity build-up in transparencies. Such agents are of three basic types: (1) Metallic devices which come into contact with the transparencies conducting the static charge to earth. The surface of the material is not modified by these devices, therefore subsequent static charge can accumulate during handling; (2) Chemical additives which, when mixed with the compound during processing give a reasonable degree of static protection to the finished products; (3) Transparent metallic films which are grounded to the airframe.

arch – A freestanding structure which supports the transparency.

azimuth – The horizontal coordinate in a system of spherical coordinates, measured in a horizontal plane as an angular rotation about a fixed vertical axis.

B

band distortion – A wavy or rippling effect seen in a concentrated area of a transparency.

barium sulphate plate – A Lambertian reflector that scatters incident light in a perfectly diffusing pattern. In the measurement of haze, it is used to determine the illumination impinging on the surface of a transparency.

biaxial stretching – See *stretching; acrylic, stretched.*

binocular – Pertaining to vision with both eyes.

binocular alignment device – A device that measures the degree of binocular disparity introduced by a transparency by comparing relative differences in image location as seen by each of the two eyes.

binocular deviation – The angular difference in deviation of two parallel incident rays.

binocular field – The field of vision of the two eyes acting together.

bird impact resistant transparency (BIRT) – A transparency that is designed to withstand a bird strike while the aircraft is flying at a specified speed.

bird strike – The impact of a bird on an aircraft or aircraft transparency.

birefringence – The separation of a light beam as it penetrates a doubly refracting material, into two diverging beams commonly known as ordinary and extraordinary beams. In transparencies, this may appear as rainbowing, or the apparent random dispersion of light into its component colors.

blister – An imperfection; a relatively large bubble or gaseous inclusion. See *defects, minor optical.*

bolt hole crack – A crack in the transparency at or near the bolt hole (normally cannot be detected by ordinary visual inspection).

bondline – Common surface of adjacent laminae joined by a bonding process.

boresight – To align the sighting device on an aircraft (Head-Up- Display, gunsight) to be coincident with the bore of a weapon or a detection device (gun, rocket, missile, radar, video camera, flir).

bow frame – See *arch.*

bow tie – Diffraction streaking. See *streaking.*

break pattern – A characteristic of glass which causes it to break into pieces of variable size and sharpness as temper and the amount of stress at fracture is varied.

brightness – (1) A subjective assessment of the amount of light that appears to be emitted by a body. (2) Quantitative term more correctly referred to as luminance or luminous intensity.

buffing – The process by which the surface of a material is brought to a high polish, usually through the use of a buffing compound applied by a rotating cloth wheel.

bulk modulus (modulus of compression) – The ratio of hydrostatic pressure to the change in volume per unit volume.

bull's-eye – A localized depression or bulge in a transparency surface creating a lens like defect which produces optical distortion.

bus bar – One of a set of electrical conductors used to transmit power to the edge of the heated area of a transparency.

butt line – A series of longitudinal vertical planes that are used to locate a point to the left or right of the center of a fuselage. The center line (axis of symmetry) is 0.

C

canopy – (1) The transparency of the aircraft which provides vision primarily to the side and overhead areas. (2) A single transparency that encloses the entire aircraft cockpit.

case depth – The compressive layer thickness of thermally tempered or chemically strengthened glass.

casehardened – A process of hardening a substance so that the surface layer or case is made substantially harder than the interior or core. Also, a term sometimes used for tempered glass.

cast – (1) To form a plastic mass into a specific shape by setting in a mold; (2) To form a plastic film or sheet by pouring liquid resin onto a moving belt or by polymerizing between glass plates.

casting – The finished product of a casting operation producing a definite shape.

catalyst – A substance that accelerates the cure of a resin system without generally being affected chemically.

central tension – The magnitude of tension within glass resulting from thermally tempering or chemical strengthening.

chemical tempering – An ion exchange process which puts larger ions into the outer surface of glass, putting the outer surfaces into compression and the interior of the glass in tension. This process is capable of producing a higher degree of surface compression than the practical limits of thermal tempering.

chip pulling – Tendency of an interlayer or seal to shrink as a result of cold exposure and pull chips from the surface of glass, either by shear or tension or both. Primarily found in glass/PVB laminations.

chromatic – Of or relating to color; perceived as having a hue; not white, gray, or black.

CIP (Cast-in-place) – A term used to identify a type of interlayer material that is poured between the transparent face sheets of a fabricated part and cured as a component part of the assembly.

clamshell – Intralaminar cracking found in materials.

clearview – A window that is opened to provide a clear view when the front windshields are iced over or obliterated due to birdstrike. The pilot uses this window to land the aircraft.

coating, abrasion resistant – A protective coating to minimize surface damage. See *hardcoat, coating, protective.*

coating, anti-reflective – A thin film applied to a transparency surface to reduce its reflectance.

coating, E-C – An electrically conductive thin film deposited on a transparent material; used on windscreens as the heating element and to dissipate static charge.

coating, high-reflecting – A broad class of single or multilayer coatings that are applied to a surface for the purpose of increasing its reflectance over a specified range of wavelengths. Single films of aluminum or silver are common; but multilayers of at least two dielectrics are used when low absorption is required.

coating, P-static – Thin conductive coating used to bleed off static electrical charge buildup on a transparency. (Also called antistatic coating).

coating, protective – Films that are applied to a coated or uncoated optical surface primarily for protecting the surface from mechanical abrasion, chemical corrosion, or both.

coefficient of expansion – The fractional change in the length or volume of a body per degree of temperature change. See *thermal expansion.*

cohesion – The state in which the particles of a single substance (such as an adhesive or adherend) are held together by chemical forces.

cold box – A chamber used to test parts for low temperature stability and heat uniformity.

cold dispatch – The ability of a windshield system to meet the certification requirements at a specified temperature without artificial heating. The capability may also be specified at a reduced speed as an emergency procedure.

cold flow – Creep at room (ambient) or lower temperatures.

collimate – To render light rays parallel.

collimation – The process of aligning the optical axis of optical systems to the reference mechanical axes or surfaces of an instrument; or the adjustment of two or more optical axes with respect to each other. The process of making light rays parallel.

collimator – An optical device which renders diverging or converging rays parallel. It may be used to simulate a distant target, or to align the optical axes of instruments.

color – The sensation produced by light of different wavelengths throughout the visible spectrum.

composite windshield – A windshield composed of layers of plastic and glass or of different plastics, which are bonded together.

concave – A term denoting a surface curved inward, as the inside of a sphere or circle.

conductivity, electrical – The reciprocal of electrical resistance.

conductivity, thermal – Time-rate of heat transfer through a unit volume at a unit difference in temperature.

contrast – The ratio or other numerical representation of the difference in photometric brightness between two stimuli fields or surfaces.

convergence – The bending of light rays toward a single point.

convex – A surface curved outward, as the exterior of a sphere or circle.

copolymer – A polymeric system comprised of two or more different monomeric units.

core ply – The primary structural ply of a transparency.

coupon – A sample of material used for testing.

crack propagation resistance – A measure of the work, other than that resulting in permanent deformation, which is absorbed per unit nominal area of crack extension, determined at the time when a creeping natural crack leaps forward. This property is sometimes called *fracture toughness*. See *K-value, toughness*.

crazing – A series of small defects which appear as fissures or fine cracks on or under the surface of but not extending entirely through the material. In plastics, true crazing is the condition just prior to crack formation, and is an area of low density which manifests a difference in refractive index.

creep – The slow deformation of a material under stress.

crew shield – See *spall shield*.

critical optical area – Area of a windscreen or canopy that requires a high degree of optical quality, as defined by drawings or specifications. It is used for gunsight, taxi, takeoff and landing. See *primary optical area*.

crosslinking – The formation of a three-dimensional network of chemical bonds, usually covalent, between polymer molecules. When extensive, as in thermosetting resins, crosslinking makes one infusible, insoluble, supermolecule of all the chains.

crown glass – A hard, easily polished, highly transparent optical glass with high refraction and low dispersion.

crystal – A state of molecular structure in some resins which denotes stereo-regularity and compactness of the molecular chains forming the polymer.

cure – The achievement of certain physical properties of a material by chemical reactions; usually accomplished by the action of heat, radiation, catalysts, or a combination thereof with or without pressure.

D

daylight opening – All of the transparent area of the finished part.

definition – The sharpness of imagery produced by an optical system.

degree of polymerization (DP) – The number of structural units, or "mers," in the polymer molecule in a particular sample. The value is obtained from the molecular weight of the polymer divided by that of the mer. If average molecular weight is used, then the value is the average DP. In most polymers the DP must reach several thousand if worthwhile physical properties are to be achieved.

delamination – The separation of the layers in a laminate into its constituent parts, due to the failure of the adhesive or resin binder, caused by moisture ingress, mechanical and/or thermal stress, and chemical UV degradation of the adhesive layer.

delamination, edge – Separation of the layers of a material at the edge of a laminate.

delamination, internal – Separation of the layers of material in a laminate other than at the edge.

deletion (isolation) lines – Scribed or etched lines which divide the EC coating into separate areas for heating control.

density, optical – Logarithm to the base 10 of the reciprocal of diffuse transmittance.

design eye – Reference point in aircraft design from which all anthropometric design considerations are taken (the designed location of the pilot's eye).

deviation – The deflection of a ray of light passing through a transparent medium caused by non-parallism of opposite surfaces. Measured in angular milliradians, prisms, or in prism diopters. It is a function of the angle of incidence at each thickness of material and the index of refraction of the material. See *angular deviation.*

di-butyl sebacate (DBS) – A liquid plasticizer for polyvinyl butyral which converts it to an interlayer.

dichroic glass – A glass which will transmit some colors and reflect others, or which will display certain colors when viewed from one angle and different colors when viewed from a different angle.

dichroic materials – Materials which exhibit dichroism.

dicing – The violent breakage of full thermally tempered or chemically tempered glass or glass ceramic which produces particles with no dimension greater than the thickness of the material. Particle size is dependent on the degree of temper and stress at fracture.

dielectric strength – The maximum electrical gradient a dielectric material can withstand without failing; expressed in volts per thickness.

diffraction – The bending of light waves around an obstacle.

diffraction streaking – See *streaking.*

diffusion – A scattering of light by reflection, diffraction, or transmission. Diffuse reflection results when light strikes an irregular surface such as a frosted window or the surface of a frosted or coated light bulb. When light is diffused, no definite image is formed.

diffusivity, thermal – The measurement of heat flowing through a unit area of a substance per unit of time, divided by the product of the specific heat, density and temperature gradient in the material.

dig – Deep, short scratches on the surface of glass. See *scratches.*

disparity – See *binocular disparity.*

dispersion – The process by which rays of light of different wavelength are deviated angularly by different amounts as, for example, with prisms and diffraction gratings. The term dispersion is also applied to other phenomena which cause the index of refraction and other optical properties of a medium to vary with wavelength.

displacement – (1) In passing through a window with parallel surfaces, light rays are bent and displaced. The displacement is zero for 0 angle of incidence, and increases as the angle of incidence, thickness, or index of refraction are increased. The displacement is linear and usually measured in millimeters or fractional inches. It does not increase with distance and the effect on pilot vision probably is not significant. (2) The image offset caused by refraction of light as it passes through a transparency. See *lateral displacement.*

displacement grade – A measure of optical distortion made from photographs of grid-board images taken through aircraft transparencies. The measure is typically made directly on a photographic print and measures the maximum displacement of a distorted line (horizontal and vertical) with respect to its undistorted orientation. The measure does not take into account the total displacement of the distorted line from its undistorted image, nor does it consider the length or angular width of the distorted line. In some cases the horizontal and vertical worst cases from defined areas are geometrically added to produce a factor of severity which is used for specification limits.

distortion – The rate of change of deviation resulting from non parallel surfaces in a transparent part. Expressed as the angular bending of the light ray per unit of length of the part, for example, milliradians per centimeter. May also be expressed as the slope of the angle of localized grid line bending, for example, 1 in 5.

distortion, radial – A change in magnification from the center of the field to any other point in the field, measured in a radial direction to the center of the field. "Barrel distortion" results when the magnification decreases with field angle; "pincushion distortion" results when the magnification increases with field angle.

divergence – The bending of light rays away from each other.

double image – (1) Two images of an object resulting from severe localized distortion. (2) The perception of two images from a single object due to excessive binocular disparity.

drape forming – Method of forming a thermoplastic sheet in which the sheet is clamped into a movable frame, heated and draped over high points of a male mold.

dry seal – A pressure or weather seal which is molded and cured; may be a component of the transparency or the support structure.

ductility – The extent to which a solid material can be deformed by elongation without fracture.

E

EC coating – See *coating, E-C.*

ECM – (1) "Electronic countermeasure(s)." (2) "Electronic countermeasure mission."

edge attachment – The means of fastening the edges of a transparency to the aircraft structure. Also includes expansion joints and any other connection between the transparency and the aircraft structure.

elastic deformation – Deformation of an object under load which disappears when the load is removed or relaxed.

elastic limit – The largest unit stress that can be developed without a permanent set remaining after the load is removed.

elasticity – The ability of a material to return to its original size or shape after having been stretched, compressed or otherwise deformed. If the strain is proportional to the applied stress, the material is said to exhibit Hookean or ideal elasticity.

electrochromic – A material property which results in a change of color when electrically excited.

elevation – An angle in the vertical plane.

elongation – The fractional increase in a material's length due to stress in tension or to thermal expansion.

emissivity – The capacity of a body to emit radiation.

emittance, spectral – A term which usually refers to radiant emittance as a function of wavelength.

EMP – Electro Magnetic Pulse. High intensity, short duration, electromagnetic field which can couple into electrical systems and induce high voltage and current transients.

enclosure – The complete assembly, including transparency, edge attachments, frames, fairings, side beams, seals, etc.

enclosure, transparent – Any aircraft windscreen, canopy or window.

environmental stress cracking (ESC) – The susceptibility of a material to crack or craze under influence of environmental exposure and mechanical stress.

EOP – Edge of part.

ev – Electron volt; a unit of electrostatic energy. It is not a measure of potential difference.

eyebrow – A small transparency usually directly above and slightly forward of the pilot's head but aft of the windscreen.

F

fatigue – The failure of a material under repeated stress. See *environmental stress cracking.*

faying surface – The surface of an object in contact with a bonding agent.

field of view – In general, the maximum cone or fan of rays passed through an aperture and measured at a given vertex. In an instrument, field of view is synonymous with true field.

field of vision – The total three dimensional space within which objects can be seen by moving the eyes and the head.

fish eye – A bubble on the formed surface of transparent or translucent plastic materials, appearing as a small globular mass.

float glass – Glass which has had the surfaces formed by floating in a continuous ribbon on the surface of a bath of molten tin in a controlled atmosphere. This form of glass has largely replaced plate glass.

fuselage station – A series of vertical planes that are used to locate a point along the fore-aft direction of an airframe.

G

glare – The dazzling sensation of relatively bright light that interferes with optimal vision. The sensation produced by brightness within the visual field that is sufficiently greater than the luminance to which the eyes are adapted so that it will cause annoyance, discomfort, or loss in visibility.

glare, reflected – Glare resulting from specular reflections off of polished or glossy surfaces in the field of view.

glass – An amorphous inorganic product of fusion, usually transparent or translucent, consisting ordinarily of a solution of silicates that has cooled to a rigid condition without crystallizing.

glass, optical – A glass, whose composition, melting, heat treatment, and other processing is carefully controlled during manufacturing to satisfy optical specifications such as index of refraction, dispersion, transmittance, spectral transmittance, freedom from birefringence, permanence, etc., based on the application for which it is to be used.

glass transition temperature (Tg) – The temperature region in which the amorphous polymer changes from a glassy solid to a soft rubbery material. The measured value of the glass transition temperature depends to some extent on the method of testing.

glazing – Act of furnishing or fitting with a glass or a plastic transparency.

glint – A bright, reflected flash or beam of light.

gridboard – An optical evaluation tool used to detect the presence of distortion in windscreens. It is usually a vertical rectangular backboard with horizontal and vertical intersecting lines with maximum contrast between the lines and background.

grid line slope – An optical evaluation method of determining the slope of a deviated grid line to that of a non-deviated grid line. The degree of deviation is indicated by a ratio, *e.g.,* 1:2, 1:8 or 1:16. (The visual optical quality improves as the ratio gets smaller.)

H

hair line crack – A fine crack having no apparent width.

halation – The scattering of light by the transparency into the viewer's line of sight, reducing the perceived contrast of external objects. See *haze*.

hard coat – A surface coating that is intended to make the transparency more durable under adverse conditions.

haze – Ratio of the scattered light to the total light that comes through the transparency.

haze index – The ratio of corrected veiling luminance created by the transparency to the illumination impingent on its surface.

haze meter – A device used to measure haze.

haze ratio – The ratio of the haze index to the transmission coefficient (measured at installed angle). A number indicating relative clarity of a transparent part.

heat-deflection point (heat distortion) – The temperature at which a standard test bar (ASTM D 648) deflects 0.010 inches under a stated load of either 66 or 264 psi.

heat treat – The process of subjecting a material to controlled conditions of heating and cooling to develop specific properties in the material such as strength, thermal shock resistance, etc.

high polymer – A large molecule which is usually but not always comprised of repeat units of the low-molecular-weight species. Arbitrarily designated as having a molecular weight greater than 10,000.

hoop – An edge attachment which conforms to the station loft line profile of the fuselage. See *rail*.

I

illuminance – The internationally accepted photometric term for the intensive property of the luminous flux passing through a cross section of a beam, or falling on an illuminated surface. Units: lumens per square foot (foot- candle) or lumens per square meter (lux).

impact resistance – Resistance of a material, laminate, or coating to breakage, deformation, or other damage when subjected to sharp blows or shock loading. It is indicated by the energy expended by a standard pendulum-type or falling weight impact machine in breaking a standard specimen in one blow.

impact strength – (1) The ability of a material to withstand shock loading. (2) The force necessary to fracture a given test specimen in a specified manner.

incident light – A ray of light which falls upon or strikes the surface of a transparency.

inclusions – Extraneous or foreign material within the body of the glass or plastic of the transparency.

index of refraction – (1) A number applied to transparent substances which denotes the relation between the angle of incidence and the angle of refraction when light passes from one medium to another. (2) In physical terms, the ratio of the velocity of light in a vacuum to the velocity of light in the material under consideration.

infinity, optical – A term used to denote a distance sufficiently great so that light rays emitted from a body at that distance are for all practical purposes, parallel.

infrared (IR) – The electromagnetic radiation beyond the red end of the visible spectrum. The wavelengths range from .786 microns to 1 millimeter. Referred to as *IR radiation.*

installed angle – The part attitude as installed in the aircraft. Defined by the angle from a horizontal line to the vertical plane of the part, and the angle of sweep back from a horizontal line normal to the center line of the aircraft.

interferometer – An instrument employing the interference of light waves for purposes of measurement; such as determining the accuracy of optical surfaces by means of Newton's rings, and the measurement of optical paths, and linear and angular displacements.

interlayer – A transparent flexible material used as a thermally compensating layer and adhesive between separate plies of a transparency. In a laminated transparency, each interlayer is considered a separate ply. The interlayer may add to the toughness, ductility and impact resistance of composite glazings. See *CIP, Di-Butyl Sebacate (DBS), PVB.*

internal reflections – Reflections of light or bright objects inside the crew station that enter the pilot's eyes by way of the inside surface of the transparency.

izod impact test – A test designed to determine the relative resistance of a plastic material to a shock loading. It may or may not involve the notching of a specimen, which is then placed in the jaws of the machine and struck with a weighted pendulum. See *impact strength.*

J

K

K-Factors – A measure of the toughness or crack propagation resistance of material. Originally applied to acrylic but being evaluated for application to polycarbonate.

K-Value – The ratio of power dissipated at either the hot spot or control point to the average of the entire heated area for electrically conductive coatings. $K_A = \frac{\text{average power}}{\text{power at control spot}}$ $K_H = \frac{\text{power to hot spot}}{\text{power at control spot}}$ $K_M = \frac{\text{average power}}{\text{power at hot spot}}$

L

laminar shear strength – The shear strength parallel to the laminar plane of a composite. Also, in stretched acrylic, the shear strength parallel to the principle surfaces.

laminar tensile strength – Flatwise tensile strength perpendicular to the laminar planes.

laminate – The process of bonding two or more plies of transparent plastic or glass with or without an adhesive. The transparent laminates used as glazing materials consist of two or more sheets of transparent plastic or glass bonded with or without an adhesive. The reinforced laminates used for edge attachment consist of one or more layers of reinforcing materials such as glass cloth or synthetic fabric cloth impregnated with a laminating resin. When the resin is cured, the resulting laminate may have better properties than either component material. In some instances the laminating resin, if cured in contact with the glazing material, may act as an adhesive between the glazing material and the reinforced laminate. Reinforced laminates are sometimes referred to as *impregnates*.

laminated – A term used to denote a product that consists of two or more layers of material.

lapping – The finish-grinding or polishing operation on a rough surface by the use of abrasive grains usually contained in a liquid carrier or medium.

lateral displacement – The shift or movement of a light ray from its original path as it passes through a transparent material while maintaining parallelism between the original and final paths. The change in location of an image due to this change in path.

lensing – A magnification or minification of visual images which may vary in extent from one portion of the transparency to another. The inherent positive or negative dioptric power found in a curved finished transparency (i.e., windscreen, canopy).

light array – A matrix of equally spaced lights used for photographic evaluation of multiple imaging.

light box – A rear illuminated box that is used to hold target patterns for photographic evaluation of transparencies.

light, collimated – A light bundle in which the rays emanating from any single point in the object are parallel to one another. Light from an infinitely distant real source, or apparent source, such as collimator reticle, is collimated light.

light, polarized – A light beam whose electric vectors vibrate along the same direction, that is in a single plane containing the line of propagation, is said to be "plane polarized" (often called linearly polarized). If each electric vector can be broken into two perpendicular components that have equal amplitudes and that differ in phase by 1/4 wavelength, the light is said to be "circularly polarized." Circular polarization is obtained whenever the phase difference between the two perpendicular components is any odd, integral number of quarter wavelengths. If the electric vectors are resolvable into two perpendicular components of unlike amplitudes and differing in phase by values other than 1, 1/4, 1/2, 3/4, etc., wavelengths, the light beam is said to be "elliptically polarized."

line of sight (LOS) – Straight line of vision connecting the observer's eye with the observed object. Line of vision; optical axis of a telescope or other observation instrument.

linear displacement – See *lateral displacement.*

lint – The collective term for small quantities of dirt, dust, hair and fuzz, dispersed within a laminate.

luminance – The internationally accepted photometric term for the intensive property of an emitting, transilluminated, or reflecting surface (formerly called brightness). The luminous flux emitted, transmitted or reflected per solid angle per unit projected area of the surface. Units: foot-lambert, millilambert, or candle per square metre (nit).

luminous transmittance – The ratio of transmitted to incident light. See *transmittance.*

M

magnification – The increase in apparent size obtained by viewing through a lens or other optical device.

major defects – Gross distortion, chips, cracks, crazing, deep scratches, or any defect which may significantly impair visibility through the windscreen.

mark off – Surface distortions on a transparency caused during heat forming when irregularities in a form are transformed to the part being formed.

mark, scuff – Surface imperfections produced by the transfer of mold surface defects to the component during molding and forming operations.

masking – The process of protecting a transparent surface by the application of a strippable coating or by the application of heavy kraft paper or plastic film with a pressure sensitive adhesive that is not harmful to the plastic.

mechanical properties – The properties having to do with structural performance.

melt index – The amount, in grams, of a thermoplastic resin which can be forced through an orifice of defined diameter when subjected to a given force at a given temperature for a given time in minutes.

memory – A characteristic of a finished plastic part to return to its original shape once stress has been relieved beyond the forming temperature (stretched acrylic is a good example of a material with a strong memory).

methyl methacrylate – A colorless, volatile liquid derived from acetone cyanohydrin, methanol and dilute sulphuric acid and used in the production of acrylic resins.

milkiness – A condition of pronounced cloudiness in glass or plastic, usually a quality control problem.

minification – The apparent reduction of an object by a lens or other optical device.

minor defects – Imperfections such as light scratches, inclusions, bubbles, or blemishes.

modified – Containing ingredients such as fillers, pigments or other additives, that help to vary the physical properties of a plastic material. An example is oil-modified resin.

modulus of elasticity – Stress/strain ratio in a plastic material that is elastically deformed.

modulus of rupture (MOR) – The fictitious tensile or compressive stress, S, in the extreme fiber of a beam computed by the flexure equation S = Mc/I, where M is the bending moment that causes rupture, c is the distance from the neutral axis to the extreme fiber, and I is the moment of inertia of the cross-section area about the neutral axis. MOR is considered the primary measure of glass strength.

modulus of toughness – (For ductile material such as acrylic.) The area under the stress-strain curve up to the point of rupture.

Mohs' value – A measure of hardness based on a scale, established in 1822 by Frederick Mohs, giving a relative ranking of minerals in the order in which one will scratch another.

moisture-vapor transmission – The rate at which water vapor permeates through a plastic film or wall at a specified temperature and relative humidity.

mold forming – A process for forming hot glass or plastic into or over a mold with air or hydraulic pressure or by its own weight.

mold release – See *parting agent*.

mold seam – A line formed at the point of contact of the mold halves. The prominence of the line depends on the accuracy with which the mating mold halves are matched.

molding shrinkage (mold shrinkage, shrinkage, contraction) – The difference in dimensions, (measured at normal room temperature and expressed in in/in) between a molding and the mold cavity.

monochromatic – Having or consisting of one color.

monocular – Pertaining to or affecting one eye.

monocular field – Field of vision with one eye alone.

monolith – A transparency consisting of one ply of "as-received" sheet, plastic or glass.

monomer – A relatively simple molecular structure that is repeated many times in a polymer. See *polymer*.

monomeric cement – Monomer used as an adhesive; it polymerizes (thickens and hardens) under the influence of heat, light and/or catalyst in the joint.

MOR Bar – Modulus of rupture bar. Generally used to test glass strength in bending, since tensile tests are erratic.

MTBF – Mean time between failure.

MTBRR – Mean time between removal or replacement.

mud cake cracking – Surface cracking which shows a typical pattern of mud which has dried and cracked.

multiaxial stretching – See *stretching.*

multiple images – Images of external lights that result from multiple reflections off the internal surfaces of the transparency. Referred to as *ghost images.*

multiple imaging ratio – The ratio of the apparent luminance of the secondary image to the apparent luminance of the primary image. See *angular displacement.*

multiple imaging separation – The angular separation of primary and secondary multiple images as measured from the design eye position.

N

N, n – A symbol used to indicate index of refraction. It is usually used with a subscript to indicate the wavelength of light, e.g., N_D or n_D indicates the index of refraction for sodium light of 5893 angstrom wavelength. The red and green-blue lines given by the hydrogen tube coincide with the Fraunhofer lines $C(N_C)$ and $F(N_F)$ respectively.

Newton's rings – A series of rings or bands resulting from the interference of reflected beams of monochromatic light from two adjacent polished surfaces that are separated by a thin film of air.

nonoptical area – Area of a transparency with no fixed optical specification requirements. See *optical free zone.*

normal – An imaginary line forming right angles with a surface or other lines. It is used as a basis for determining angles of incidence, reflection and refraction. Sometimes called the *perpendicular.*

notch sensitivity – Term used in connection with the mechanical properties of a material to describe the extent to which the presence of a surface irregularity such as a notch, crack or scratch will increase the tendency to fracture. Low notch sensitivity is associated with ductile materials, high notch sensitivity with brittle materials.

O

ohms per square – An extensive coefficient of proportionality between electric field and surface current in a thin film coating. It is a surface property independent of the size or thickness of the film.

opaque – Not transparent or translucent; impervious to visible light, i.e., has zero luminous transmittance. A substance which is impervious to light applied to transparent or translucent substances. To make impervious to light.

open seed – A blister leaving a hole in the glass surface. See *blister*.

optical density – Logarithm to the base 10 of the reciprocal of transmittance.

optical flat window – A transparent window in which both front and back surfaces are parallel to each other within a specified tolerance.

optical free zone – Area of a transparency where there are no optical specifications. See *nonoptical area*.

optical properties – Those properties of a transparent material which pertain to the effect the medium has upon light, such as index of refraction, dispersion, homogeneity, and freedom from defects.

optical system – A combination of optical components arranged so as to perform one or more optical functions.

optics – The branch of physical science which is concerned with the nature and properties of electromagnetic radiation and with visual phenomena.

orange peel – Granular or dimpled appearance (having the apparent texture of an orange peel) of a transparency surface due to improper manufacturing.

orientation – The alignment of the crystalline structure in polymeric materials so as to produce a highly uniform structure. This can be accomplished, for example, by cold drawing or stretching in fabrication.

overcoat – A layer of material applied to a transparent part to protect it from physical or chemical damage during shipment or storage. See *masking*.

P

parallax – An apparent movement of an object against its background due to a change in position of the observer's eye or due to viewing an object first with one eye, and then with the other.

parting agent – A substance, e.g., wax, silicone oil, used to coat a mold cavity to prevent the molded piece from sticking to it and thus facilitating its removal from the mold.

parting line – Seam on a molding or casting where the two halves of a mold meet in closing. See *mold seam.*

permeability – (1) The passage or diffusion of a vapor, liquid or solid through a barrier without physically or chemically affecting it. (2) The rate of such passage.

photoelasticity – A technique for measuring the stresses and strains in a transparent material by observing the change in the double refraction of the material when it is subjected to stress.

photometer – An instrument for measuring electromagnetic radiation in the visible range.

photopic – Vision under illumination sufficient to permit the discrimination of colors. Sometimes called daylight vision.

physical optics – The branch of science which treats light as a wave phenomenon wherein light propagation is studied by means of wave fronts rather than rays.

physical properties – The properties inherent to the material such as refractive index, thermal coefficient of expansion, dielectric strength, etc.

Pilkington process – A process for making flat glass in which molten glass is drawn continously from a tank, and then passed between rolls to form a continuous sheet of prescribed thickness.

pits – Small indentations in the transparency surface.

plane – A surface which has no curvature; a perfectly flat surface.

plastic – Any of numerous organic synthetic or processed materials that are either thermoplastic or thermosetting polymers of high molecular weight and that can be molded, cast, extruded, drawn, or laminated into objects, films, filaments, or sheets.

plastic deformation – A permanent change in the size or shape of an object under stress, without fracture; opposed to elastic deformation.

plasticity – A property of a material that permits permanent and continuous deformation without rupture, upon the application of a force that exceeds the yield value of the material.

plasticize – To soften a material and make it plastic or moldable either by adding a plasticizer or by using heat.

plasticizer – Chemical agents added to plastic compositions to improve flow and processability and to reduce brittleness. This is achieved by lowering the glass transition temperature.

plate glass – Flat glass that is formed by a rolling process, and then ground and polished on both sides, with surfaces essentially plane and parallel.

plies – One of several layers that are laminated together.

polarimeter – A polariscope equipped with a half-shade device and an angular scale generally attached to the analyzer. It is used to measure the amount of rotation of the plane of polarization by materials placed within it.

polariscope – A combination of a polarizer and an analyzer used to detect birefringence or rotation in the plane of polarization of materials placed between them.

polarization – The splitting of a beam of light into two components, each vibrating in its own plane.

polarizer – An optical device for splitting a beam of light into its two orthogonal electromagnetic components, each vibrating in its own plane.

polarizing filter – A filter that polarizes the light passing through it.

polishing – The process of putting a highly finished surface on a glass or plastic surface, by rubbing it with a finely milled abrasive, such as rouge, cerium oxide, or a similar material.

polycarbonate – Tough transparent thermoplastic, characterized by high impact strength and high softening temperature, used in the construction of aircraft transparencies. Bisphenol A polycarbonate is the type currently considered for structural aircraft glazing.

polycarbonate resins – Polymers derived from the direct reaction between aromatic and aliphatic dihydroxy compounds with phosgene or by the ester exhange reaction with appropriate phosgene derived precursors. Structural units are linked by carbonate groups.

polymer – A large molecule of high molecular weight, formed by the reaction of simple molecules (mers or monomers), either by "addition" polymerization or by polycondensation (condensation polymer). (When two or more different monomers are involved, the product is called a copolymer). A polymer can usually be represented by a chain of repeating structural units, known as "mers."

polymerization – A chemical reaction in which the high-molecular- weight molecules are formed from monomers. When two or more different monomers are involved, then the process is called copolymerization or heteropolymerization.

polymethyl methacrylate – A thermoplastic polymer synthesized from methyl methacrylate. It is a transparent solid with exceptional optical properties and good resistance to UV radiation and water. It is obtainable in the form of sheets, granules, solutions and emulsions. Polymethyl methacrylate is a material that is extensively used for aircraft domes, lighting fixtures, decorative articles, etc.; it is also used in optical instruments and in surgical appliances.

polysiloxanes – Polymers that contain the Si-O linkage. Usually synthesized by the polycondensation of silanols.

polysulfides – Polymers containing sulfur and carbon linkages. An example of this type of polymer is Thiokol rubber, which is synthesized from organic dihalides and sodium polysulfide.

polysulfone – A polymer containing a sulfone linkage. These thermoplastic materials exhibit exceptional high temperature and low creep properties, have high arc resistance, are self-extinguishing and may be molded and extruded.

polyurethane resins – A family of resins produced by reacting disocyanates with glycols to form polymers. These groups, under the influence of heat or certain catalysts, will react with each other, or with water, glycols, etc., to form a tough durable material used in transparent enclosures as interlayers or face plies.

polyvinyl butyral (PVB) – A thermoplastic material derived from a polyvinyl ester in which some or all of the acid groups have been replaced by hydroxyl groups and some or all of these hydroxyl groups have been replaced by butyral groups by reaction with butyraldehyde. It is a colorless, flexible, tough solid and is used primarily in interlayers for laminated transparent material.

portable photometer – Small field portable instrument for measuring luminances.

position, installed – The angular position of a windscreen as it would be found in an aircraft.

postforming – The forming, bending or shaping of thermoset laminates that have been heated to make them flexible before the final thermosetting reaction has occurred. Upon cooling, the formed laminate retains the contours and shape of the mold over which it has been formed.

press bending – Forming hot glass or plastic between two contoured molds. Mainly for single curvature or shallow draw.

pressure forming – A thermoforming process wherein pressure is used to push the sheet to be formed against the mold surface as opposed to using a vacuum to suck the sheet flat against the mold.

press polish – A finish for thermoplastic sheet stock produced by contact under heat and pressure with a very smooth, hard material which gives the plastic a high sheen or optical finish.

primary image – The image formed by rays from an object (usually a light source) transmitted through the transparency without being reflected. See *multiple imaging.*

primer – A coating applied to a surface to improve the performance of the adhesive bond.

primary/optical area – An area of the windshield which is defined as most critical for flight vision and which is subject to the most demanding optical quality control.

proportional limit – The greatest stress a material can withstand without deviating from the law of proportionality (Hooke's Law).

P-Static (Precipitation Static) – Electrical charge built up on the outer surface of the windshield due to the impingement of charged particles. Also called *triboelectric charging.*

Q

quality, optical – Surface defects, scratch and dig rating, sphericity and related quantities are usually used to define quality of an optical element or system.

quality, surface – A means of specifying allowable flaws by comparison to reference standards of quality.

R

rail – The horizontal edge attachment of a transparency. See *sill*.

rainbowing – Colored patterns in a transparency produced by the photoelastic molecular nature of the material and stress gradients in the transparency. Certain angles and light polarizations in relation to some windscreen designs may produce localized bands of color in the transparency which can be distracting.

RCS – Radar cross-section; The display of a returned radar signal from reflective surfaces which is referred to as the signature of the target.

reflections – See *internal reflections*.

refraction – A change in the angle of propagation of a wave that occurs when it passes from one transparent medium to another.

refractive index – See *index of refraction; Snell's Law*.

residual stress – Stress locked in a transparency at the time of manufacture.

resin – Any of a class of solid or semisolid organic products of natural or synthetic origin, that are generally of high molecular weight. Resin usually refers to the essential ingredients before final processing and fabrication. Most resins are polymers.

resistance, bird – The requirement imposed on a windscreen to withstand bird impact while the aircraft is flying at a specified speed.

resistivity – The ability of a material to resist passage of electrical current either through its bulk or on its surface. The unit of volume resistivity is the ohm-cm., or surface resistivity, the ohm.

resolution – The ability of a lens or optical system to form separate images of two objects close together. The ability to optically resolve fine detail.

RH – Relative humidity. The ratio of the amount of water vapor actually present in the air to the greatest amount possible at the same temperature.

Rockwell Hardness – A common method of testing a plastics material for resistance to indentation in which a diamond or steel ball, under pressure, is used to pierce the test specimen. The load used is expressed in kilograms and a 10-kilogram weight is first applied and the degree of penetration noted. The so-called major load (60 to 150 kilograms) is next applied and a second reading obtained. The hardness is then calculated as the difference between the two loads and expressed with nine different prefix letters to denote the type of penetrator used and the weight applied as the major load.

RTV – Room temperature vulcanate. RTV rubber can be a form of silicone rubber which vulcanizes at room temperature or any temperature curing elastomer.

S

sag forming – A process by which a material is clamped only at its perimeter and formed by heating in an oven until it sags by its own weight to a predetermined depth.

salt abrasion – A method of abrading transparent material using extra-fine salt flakes which simulates high speed flight through frozen rain, snow, and light hail.

sandwich heating – A method of heating a thermoplastic sheet prior to forming which consists of heating both sides of the sheet simultaneously.

scratch – Any marking or tearing of the surface. A sharp, penetrating surface defect in glass or plastic caused by an abrasive material.

secondary image – The image resulting from internal reflection of external lights from the surfaces of a transparency. See *multiple imaging.*

semi-tempered – A term used to define tempered glass which has been tempered to approximately 1/2 the maximum strength possible for thick glass.

shatter resistance – See *crack propagation resistance, K-value, toughness.*

shear modulus – The ratio of unit shear stress to unit shear strain up to the proportional limit.

sheet (thermoplastics) – A flat length of a fused thermoplastic resin .010 inches or greater in thickness.

shimmer – The distracting visual effect of a multitude of high frequency interruptions of expected images. It can be produced by moving the eyes/head when viewing objects through a transparency.

shore hardness – A procedure for determining the indentation hardness of a material by means of a durometer. Shore designation is given to tests made with a specified durometer instrument.

sill – The horizontal edge attachment of a transparency. Referred to as *rail.*

sizing – The process of applying a material to a surface to fill pores and thus reduce the absorption of the subsequently applied adhesive or coating or to otherwise modify the surface. Also the surface treatment applied to glass fibers used in reinforced plastics. The material used is often called size.

skim – A term used to denote streaks of dense seeds with accompanying small bubbles.

sleek – An imperfection; a fine scratchlike mark having smooth boundaries, usually produced by a foreign particle in the polishing operation. See *scratches.*

slip forming – A method of forming three-dimensional parts in which thinning out is reduced by allowing the excess plastic sheeting to slip through the clamping rings while the sheet is being stretched during forming.

slip plane – Component that is built into the edge area of some aircraft laminates to act as a stress relief in low temperature exposure to prevent cold chips in glass.

slope, grid line – An optics evaluation method of determining the slope of a deviated grid line to that of a non-deviated grid line. A ratio is the index of degree of distortion, e.g., 1:2, 1:8, or 1:16. Also called slope reading.

snap-back forming – A method of forming based on the memory of transparent plastic sheets to return to their flat sheet form when hot.

Snell's Law – Snell's Law, often called the law of refraction, describes the relation between the angle of incidence and the angle of refraction of a light ray passing between media with different indices of refraction:

$$\frac{\sin \Theta_i}{\sin \Theta_r} = \frac{n'}{n}$$

where Θ_i is the angle of incidence, Θ_r is the angle of refraction, n' is the index of refraction of the medium containing the refracted ray, and n is the index of refraction of the medium containing the incident ray.

soda-lime glass – A glass containing a substantial proportion of lime, usually associated with soda and silica.

softening range – The range of temperature in which a plastic changes from a rigid to a soft state. Actual values will depend on the test method. Sometimes erroneously referred to as softening point.

spall – A small particle flaking off of a glass or plastic sheet. A spall from the inside surface of a windscreen as a result of high velocity impact could be harmful to the pilot.

spall shield – A thin piece of plastic or glass bonded to the structural ply with an interlayer, with the intention being that the interlayer will contain the broken structural ply fragments in case of fracturing, thereby protecting the crew. See *crew shield*.

star fracture – A minute radial craze usually originating from an inclusion, bubble or other microscopic defect. It can be detected as bright pinpoint reflection in oblique light.

stop drill – The process of drilling holes at the extremities of cracks to stop the propagation of the crack.

strain – Change in length per unit of original length, caused by stress on the body due to temperature changes.

streaking – The pattern observed on a windscreen produced by diffraction of a light source by many small parallel lines or scratches. Also, called *bow tie* or *arcing*.

stress – (1) Tension or compression caused by the strengthening process, incomplete annealing, temperature differences, inhomogeneity, or by forces imposed upon the object from without. (2) The force per unit area of a body that tends to produce a deformation.

stress crack – External or internal crack in a plastic caused by tensile, or shear forces. The development of such cracks is frequently accelerated by the environment to which the plastic is exposed. The stresses that cause cracking may be present internally, externally or a combination of both. Appearance of a network of fine cracks is often called *crazing.*

stress, internal – The tension, compression, or shear stresses within an optical element usually caused by cooling, incomplete annealing, or chemical strengthening.

stretched acrylic – Acrylic sheet that has been heated and then stretched 60% to 80% either biaxially or multiaxially to improve its craze resistance and reduce notch sensitivity.

stretch forming – A sheet-forming technique in which the heated thermoplastic sheet or metal is stretched over a mold and subsequently cooled.

stretching – Stretching a heated plastic sheet either in two perpendicular directions (biaxial) or in all directions (multiaxial) in the plane of the sheet to improve the physical properties by orientation of the molecules.

stria – (1) A defect in optical materials consisting of a sharply defined streak of transparent material having a slightly different index of refraction than the body of the material. (2) A cord of low intensity generally of interest only in optical glass and plastic.

substrate – Basic surface on which a material adheres.

surface haze – That portion of haze (light scatter) caused or induced by properties or degradation of the surfaces of transparent parts.

T

temper – (1) The degree of residual stress in glass measured polarimetrically or by polariscopic comparison with a standard such as one or more strain disks. (2) Term sometimes employed in referring to tempered glass.

thermal conductivity – Ability of a material to conduct heat; quantity of heat that passes through a unit cube of a substance in a unit of time when the difference in temperature between the two faces is one degree.

thermal expansion (coefficient of) – The fractional change in length (sometimes volume specified) of a material for a unit change in temperature.

thermal stress cracking (TSC) – The cracking or crazing of a material caused by exposure to elevated temperatures.

thermal tempering – A process of heating glass to near its softening points and rapidly cooling it under rigorous control to achieve its increased strength tempered characteristics. Thermally tempered glass can range from "annealed" to "full," with semi-tempered glass being approximately midway between the two.

thermoforming – Any process of forming thermoplastic sheet into a desired contour of shape that consists of heating the sheet and contracting it with mold surface, or other means of creating the required shape. Once the plastic cools, it retains this contour.

thermoplastic – (1) Capable of being repeatedly softened by heat and hardened by cooling with little change in properties. (2) A material having a linear macromolecular structure that will repeatedly soften when heated and harden when cooled. A plastic that is thermoplastic in behavior. Typical of the thermoplastics family are the styrene polymers and copolymers, acrylics, cellulosics, polyethylenes, nylons, polycarbonates, some urethanes and a variety of fluorocarbon materials.

thermosetting – The property of a material to change into a substantially unfusible or insoluble product when cured either by application of heat or by chemical means. A cured thermosetting material cannot be remelted without destroying its characteristics.

tin float – A process in which the molten glass is floated on molten metal at a sufficient temperature to heat polish while the opposite side is flame polished. See *float glass.*

torsional shear – Shear yield strength of adhesive bonds determined by applying torsional shear loads.

toughness – A measure of a material's ability to absorb energy before fracture (a strong feature of polycarbonate material).

translucent – Transmitting and diffusing light so that objects beyond cannot be seen clearly.

transmission – (1) The process by which incident flux leaves a surface or medium on a side other than the incident side. (2) The ratio of the amount of radiant energy leaving the last surface of an optical system to the amount of radiant energy incident on the first surface.

transmissivity – The ratio of the intensity of light emerging from a transparency to the intensity of the light incident upon it. Also referred to as *luminous transmittance.*

transmittance, diffuse – The transmittance measured with diffusely incident flux. Also, the ratio of diffusely transmitted flux leaving a surface or medium to the total incident flux.

transmittance, internal – The ratio of the flux incident on the second surface of a medium to that transmitted by the first.

transmittance, luminous – The ratio of the luminous flux transmitted by an object to the incident luminous flux. See *transmittance.*

transmittance, radiant – The ratio of the radiant flux transmitted by an object to the incident radiant flux (the rate of flow of any radiation).

transmittance, spectral – Transmittance for a specific wavelength of incident light.

transparency – An optically clear structure which is a component of the windscreen or canopy assembly.

triboelectricity – A charge of electricity generated by friction.

U

ultraviolet (UV) – Rays of radiant energy immediately beyond the violet end of the visible spectrum, between 100 and 390 nanometers, which are deleterious to the human eye.

ultraviolet-absorbing material – A transparent material in which the spectral transmittance at any wavelength in the 290-330 nanometers wavelength band does not exceed five percent when measured on a specimen 0.250 inch thick.

uniaxial stretching – A process used in the manufacture of certain films that also makes them birefringent by virtue of the molecular orientation after stretching in one direction only.

uniform density – In a transparency, the property of attenuating visible light consistently throughout the part.

UV stabilizer (ultraviolet) – Any chemical compound which, when mixed with a thermoplastic material, protects the polymer by removing the energy absorbed by the polymer before degradation can occur.

V

vacuum forming – Method of sheet forming in which the plastic sheet is heated and drawn down by a vacuum usually into a mold. In a general sense, it is sometimes used to refer to all sheet-forming techniques, involving the use of vacuum and stationary molds.

veiling glare – Glare produced by light distributed over the visual field so as to cause reduced contrast and therefore reduced visibility. Sometimes called *veiling luminance.*

vents – (1) A hole, slot or groove in a mold provided to allow air and gas to escape during the molding operation. (2) Small fractures in glass or plastics.

virtual image – If a bundle of rays having a given divergence has no real or physical point of intersection of the rays, then the point from which the rays appear to proceed is called the virtual image. The distance of the virtual image is inversely proportional to the divergence of the rays. Since there is no physical intersection of rays there is no real image that can be focused on a screen. The image of any real object produced by a negative lens or convex mirror is always virtual. The image produced by a positive lens of an object located within its focal length is also virtual.

visco elastic – Having both viscous (liquid like flow) and elastic properties.

visible spectrum – The portion of the electromagnetic spectrum to which the retina is sensitive and by which we see. Extends from about 380 to about 760 nanometers in wavelength.

vision, binocular – The simultaneous use of both eyes in the process of vision.

visual angle – The angle subtended by an object on the retina.

visual field of regard – The total space within which objects can be seen by moving the eye, with the head stationary. See *field of vision*.

visual range – The distance where the contrast between object and background of the sky becomes imperceptible owing to aerial light.

volume haze – (1) The portion of haze caused or induced by properties or degradation of the material bounded by the two exterior surfaces of transparent parts. (2) The portion of haze not due to surface effects.

volume resistivity (specific insulation resistance) – The electrical resistance between opposite faces of a 1 cm cube of insulating material. It is measured under prescribed conditions using a direct current potential after a specified time of electrification. It is commonly expressed in ohm- centimeters. The recommended test is ASTM D257.

V_{50} protection ballistic limit – The velocity at which a specified projectile has a 50% chance of penetrating an armor panel.

W

warm forming – A process of forming a pane from stretched acrylic at a temperature low enough to prevent relaxation toward its original unstretched form.

warp – Large out-of-plane surface irregularity.

waterline – Intersection of the body exterior profile and a horizontal plane, often used as synonymous with water level, thus WL 0 is the lowest point of the body and all subsequent slicing planes are parallel to the prime longitudinal axis or other horizontal reference.

waviness – A wave-like unevenness or out-of-plane area in the surface of a plastic.

weathering – Deterioration of a material's surface during exposure to atmospheric conditions.

wedginess – Departure of the surfaces of a transparency from parallelism resulting in a prism or wedge effect. Usually expressed in minutes or seconds of arc, or in interference fringes per inch.

wet seal – A weather or pressure seal which is applied uncured to a surface at installation or to a joint after installation.

windshield – The transparency on the aircraft used for forward vision in taking off, flying, and landing; usually made of laminated glass or plastic, also known as a windscreen.

X,Y,Z

Young's modulus of elasticity – The ratio of tensile stress to strain within the elastic limit of a solid body.

yield value (yield strength) – The lowest stress at which a material undergoes plastic deformation. Below this stress, the material is elastic; above it, viscous.

zone, critical – Designated area of a windscreen used for gunsight, taxi, takeoff and landing. See *critical optical area*.

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

CHARLES BATES, JR.
Director, Human Engineering Division
Armstrong Aerospace Medical Research Laboratory

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This report is a summary of the specification requirements for optical quality for several military aircraft transparencies. It is intended to provide the design engineer with an easy reference to a majority of the accumulated historical information concerning optical quality.

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SUMMARY

This report is prepared in an effort to combine and condense information on the optical parameters used to describe the quality of an aircraft transparency. The first portion of this report defines and clarifies these parameters so that the reader may gain a further understanding of their meaning. The parameters that will be addressed in this report include:

Angular Deviation

Optical Distortion

Luminous Transmittance

Haze

Major and Minor Optical Defects

Miscellaneous Effects

Acceptable limits have been derived over time for the parameters listed above so that the optical quality of an aircraft transparency may be better defined. This report will also include a condensed version of these acceptable limits for 13 different aircraft transparencies currently in the defense inventory. There is also a chart of miscellaneous physical data which describes the transparency for 11 of the 13 aircraft.

PREFACE

This report was prepared under Work Unit 71841802 by personnel of the Crew Systems Effectiveness Branch of the Human Engineering Division, Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio 45433-6573. Acknowledgement is given to Laura L. Mulford and Martha A. Hausmann for their assistance in preparing this report. Also, acknowledgement is given to Dr H. Lee Task for his invaluable technical assistance.

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LIST OF FIGURES

FIGURE

INTRODUCTION

This report is intended to serve as a reference for understanding the major optical effects encountered in specifying aircraft transparencies. It will provide the reader with useful information for establishing specifications for an aircraft windscreen by reviewing and comparing the broad range of current designs, optical requirements, and test methods. It also serves as a quick reference to the optical requirements of modern aircraft transparencies.

The report is divided into the following categories.

1. A discussion of the cause and effect of various optical phenomena related to aircraft transparencies.

2. An abbreviated listing of optical requirements taken from 13 military windscreen specifications.

3. Windscreen configurations, dimensions, and material make-up.

BACKGROUND

Aircraft windscreens must be constructed of thick materials and shaped into extreme geometries, due to aerodynamic design considerations and birdstrike protection requirements. These extreme configurations introduce various optical effects that alter the pilot's view through the transparencies. The degree of degraded visual performance caused by these optical effects is important to determine and control since they can adversely impact mission accomplishment and safety.

In reviewing the history of windscreen specifications and measurement, it is easy to see that optical quality has been difficult to define and measure. The level of acceptability has also been difficult to establish and quantify. To date, many efforts have been made to define optical parameters that can be tested in order to increase pilot performance and these efforts have met with some degree of success. A methodology has evolved that takes into account past mistakes and includes a significant amount of newly acquired knowledge including maintenance practices in the field.

OPTICAL PROBLEMS WITH WINDSCREENS

For tactical reasons, modern day, high performance aircraft are required to fly high speed, low altitude missions. The high speed capability requires that the windscreen design offer reduced aerodynamic drag by presenting minimum angle resistance to the airstream. The low altitude capability requires a windscreen that is relatively thick in order to reduce the potential damage from bird impact. Consequently, windscreen design involves a trade-off between reduced aerodynamic drag, birdstrike protection, and visibility.

The resulting compromise is usually a thick, curved, multi-layered plastic surface intersecting the pilot's line of sight at a shallow angle. The geometry of such an optical element results in significant optical problems due to the refraction of light incident upon the angled surfaces. Additionally, flaws introduced in the manufacturing process and from service wear and abuse contribute to the visual problems the pilot experiences.

OPTICAL EFFECTS

Over time, various windscreen optical parameters have been identified and defined. They can be summarized categorically as follows:

Angular Deviation
Optical Distortion
Luminous Transmittance
Haze
Major and Minor Optical Defects
Miscellaneous Effects

The following pages will elaborate upon the optical phenomena associated with each of the parameters outlined above. In addition to their cause and effect, the discussion will include measurement techniques and miscellaneous suggestions.

Angular Deviation

Definition: The angular displacement of a light ray from its original path as it passes through a transparent material, expressed as an angular measurement (degree, minutes of arc, milliradians).

Angular deviation is an optical effect that causes objects seen through a transparency to appear displaced from their true location. In passing through each transparent surface of the windscreen, light rays are bent (refracted) and thereby may deviate in angle from their original path as they reach the eye. The effect is the same as in looking at a goldfish in a clear pond. The image of the fish does not appear where the fish is located due to the deviation caused by the water. The amount of deviation is a function of the index of refraction of the transparent material and the angle between the observer's line of sight and the transparent surfaces.

To fully understand angular deviation, it is important to recognize a distinction between angular deviation and another phenomenon called lateral displacement. In order to illustrate, Figure 1 depicts a light ray refracted by a transparency section that has parallel surfaces. The path of the ray is not changed in angle with these parallel surfaces, because the refraction angles are equal and opposite. This image shift is known as lateral displacement, as opposed to angular deviation. The shift in location of an image due to lateral displacement is constant with distance so the amount of error (d) is very small. (Lateral displacement is under the category entitled MISCELLANEOUS EFFECTS, but is described here for

purposes of clarity). In Figure 2, the surfaces are not parallel. The unequal refraction angles result in a net angular change (alpha) in the path of the ray. This is angular deviation. The shift in location of an image due to angular deviation can become very significant with an increase in distance. Angular deviation can be caused by changes in thickness or curvature across a transparency. As windscreen designs become thicker and more severely angled, angular deviation begins to contribute significantly to inaccurate target aiming.

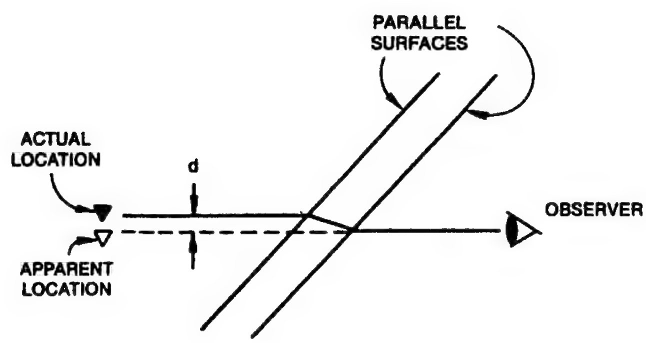


Figure 1. Lateral Displacement

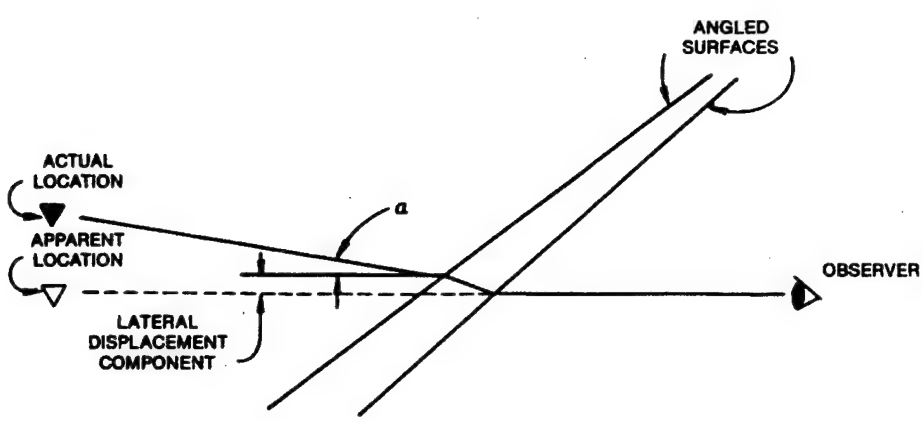


Figure 2. Angular Displacement (d)

Test Method: There have been several techniques devised to measure angular deviation. Virtually all of them measure the change in location of a point (image) when the windscreen is set into place and then removed. A number of measurements may be required to verify that a given windscreen is optically suitable because the angle between the pilot's line of sight and the transparent surface will vary across the windscreen. Details of this test procedure are given in ASTM 801-83.

The area of greatest concern is usually the gunsight area. Although angular deviation errors are not usually large in this area, their effects can be devastating. The slightest angular deviation here can translate directly into sighting errors unless accurately compensated for. For this reason, methods to measure angular deviation in this critical zone should be carefully chosen for aircraft that will have a Head-Up Display (HUD). Error data must reflect pure angular components and not be contaminated by lateral displacement errors.

Recalling earlier discussion, lateral displacement errors are insignificant at great distances. However, in a laboratory environment, test distances are necessarily abbreviated and lateral displacement errors could be the cause of a significant portion of the total image shift. Only test set-ups that employ some means to measure image shift at optical infinity will yield pure angular deviation error data. Accurately compiled error information can then be compensated for in the aircraft's weapon delivery computer or by optical means. An excellent reference that discusses methods to measure angular deviation, including ones that give pure error data, is AMRL-TR-82-43.

Optical Distortion

Definition: The rate of change of angular deviation resulting from an irregularity in a transparent part. This may be expressed as the angular bending of the light ray per unit of length of the part (i.e., milliradians per centimeter). It may also be expressed as the slope of the angle of localized grid line bending (i.e., 1 in 5).

Optical distortion can be thought of as the continuous change of angular deviation across a transparency. The effect of viewing through all points of the windscreen at the same time does more than cause the image of an object to be misplaced. If the effects of refraction across a windscreen are varied, objects can be magnified, minified, lengthened, foreshortened, misshaped, widened, narrowed, etc. The image one sees in a Funhouse mirror is an appropriate, but extreme, example of these effects.

Optical distortion is caused by a wide variety of things - changes in thickness, changes in curvature, changes in shape, heat induced stress, physical stress, etc. In general, anything that changes the refractive properties across a transparency will introduce distortion. In Figure 3, variations in thickness and curvature result in a continuous change in angular deviation (Distortion) as viewing angle is changed.

In addition to affecting the apparent size and shape of stationary objects, optical distortion can also cause moving objects to appear to vary in shape and motion in an irregular way as they are seen passing through different viewing areas of the windscreen. The net effect is a hindrance to the pilot and an additional burden for one already under a heavy workload.

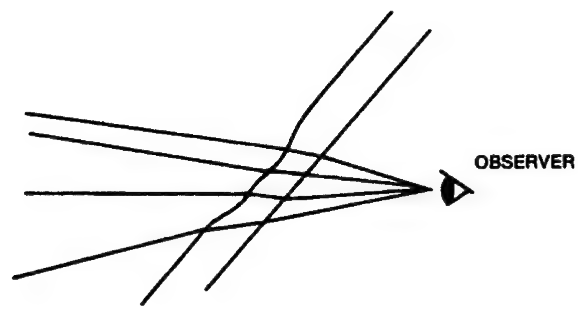


Figure 3. Distortion (Effects exaggerated)

Test Method: The method most often employed to assess the degree of optical distortion in a transparency utilizes a photographic procedure. A camera is placed at the pilot's eye position and a photograph is taken through the windscreen of a large, lighted gridboard. The horizontal and vertical elements of the grid are evenly and accurately spaced. A second exposure is then made on the same film frame with the windscreen removed. The distortion characteristics of the transparency become evident upon examining the shifted grid line spacing. Test set-up procedures, fixture sizes, spacing, and test distances are quite similar, if not the same, for most aircraft systems. The degree of distortion in a given area of the windscreen is indicated by the rate at which a grid line is bent. (Termed "Grid Line Slope" which is the x to y ratio of position change.) Details of this test procedure are given in ASTM 733-81.

Luminous Transmittance

Definition: The ratio of the intensity of light emerging from a transparency to the intensity of light incident upon it.

In simple terms, luminous transmittance relates to the amount of light that "gets through" a given transparency. That which does not get through is absorbed within the transparent material or reflected from any surfaces where a change in index of refraction occurs. A reduction in luminous transmittance is equivalent to turning down the lights, a clear disadvantage in situations where ambient light levels and/or image contrast levels are low.

Testing Method: Luminous Transmittance is measured using a photometer and a calibrated light source. The amount of light transmitted is given as a percentage of the total emitted from the source. Details of this test procedure are given in ASTM D1003.

Haze

Definition: Spatial attribute of smokiness or dustiness that interferes with clear vision. The ratio of diffuse to total transmittance of a beam of light.

As light enters or passes through a transparency, some of the light may be scattered or diffused, and may appear as haze or fog in the transparency. Haze is generally defined in terms of light scattered and, therefore, lost in passage through the transparency. In fact, the scattered light creates a veiling luminance that reduces the contrast of objects viewed through the windscreen. The most predominant cause of haze is tiny surface scratches that usually come about as a result of the cleaning process. The haze effect is increased as the angle of incidence is increased.

Test Method: A rather sophisticated test set-up is required to accurately measure haze in the laboratory. A collimated light source is used in conjunction with a device to determine the amount of scattered light. A haze figure is then calculated and expressed as a percentage. Details of this test procedure are given in ASTM D1003 and in ASTM 943-85.

Major and Minor Optical Defects

Optical defects, in general, are undesirable imperfections that occur through some combination of materials used and/or by some manufacturing procedures employed. Specifications usually impose limitations on their severity, the area they may obscure, and how objectionable they can be, in terms of visual impact. Separate rules are applied depending upon whether they are considered major or minor defects. There are many distinct defects and equally many self-descriptive terms that refer to them.

A sampling of some major terms are: deep scratches, bullseye, gouges, gross distortion, orange peel, chips, cracks, crazing, spalls, etc. (any defect which may significantly impair visibility through the windscreen).

Minor terms include: light scratches, embedded particles, inclusions, bubbles, blemishes, seeds, surface dimples, pimples, etc. (imperfections).

Acceptance criterion is usually based upon visual inspection since testing with instrumentation can be impossible or meaningless.

Miscellaneous Effects

Miscellaneous effects are undesirable optical phenomena that are, for the most part, unavoidable; however, since their visual consequences are tolerable, specifications do not presently place limits on them. Some examples are: lateral displacement, multiple images, birefringence, reflections, etc.

Lateral displacement has been described. Birefringence, also known as rainbowing, is a polarization effect. In sunlight, it may appear from within the cockpit as an apparently random dispersion of light into its component colors. The effects are not serious. Multiple images and reflections are depicted in Figures 4 and 5, which are relatively self-explanatory.

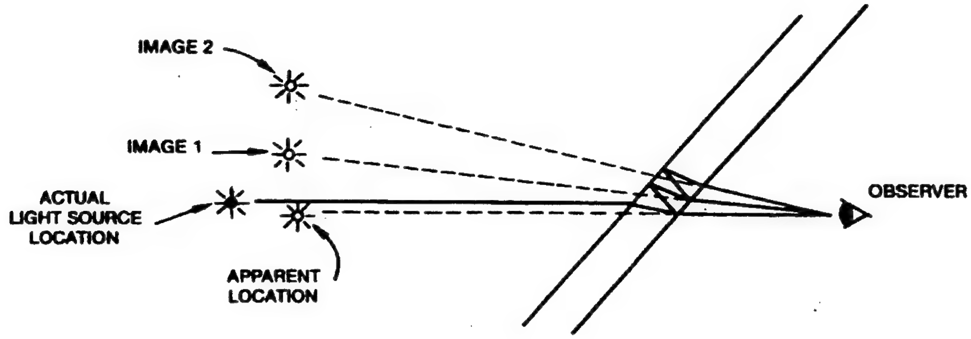


Figure 4. Multiple Images

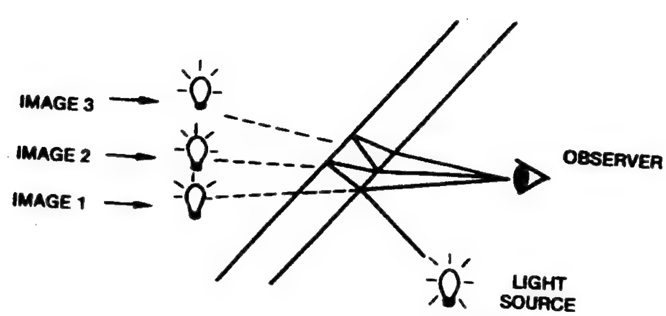


Figure 5. Internal Reflections

INDEX FOR QUICK REFERENCE TABLES

The table below is an index of page numbers for the following Optical Specifications and Physical Data for 13 primary aircraft in the current Defensive Inventory.

* The Physical Data for this aircraft include a newer configuration followed by the older configuration

\+ No Physical Data available

A-7 Optical Parameters

ANGULAR DEVIATION

Elevation .... (+) or (-) 2 mrad (6.88 min of arc)
Azimuth .... (+) or (-) 3 mrad (10.32 min of arc)

Between azimuth
viewing angles of ...... (+) or (-) 2 mrad (6.88 min of arc)
(+) or (-) 2 degrees

Deviation is measured from the following 2 positions:
1) design eye position
2) 1 inch up and 3 inches forward of the design eye position

OPTICAL DISTORTION

Maximum of 1 in 10 Grid Line Slope also when visually inspected. There shall be no immediate blurring, divergence, convergence or jumping of grid lines. Local distortion is allowable if it does not distract from aircrew performance.

LUMINOUS TRANSMITTANCE ... Minimum of 79 %

HAZE ... Maximum of 3.5 %

OPTICAL DEFECTS

Scratches ...... maximum of F-428-3 in critical optical area
...... maximum of F-428-4 in outer optical area
...... maximum of F-428-6 in 0.5 inch wide optics waived area

Orange Peel .... visual inspection judged to cause impairment

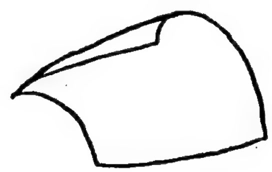
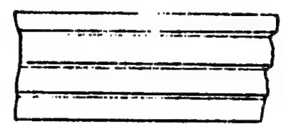
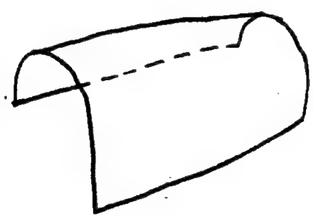
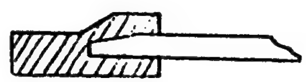
MINOR OPTICAL DEFECTS

Critical Optical Area .. maximum of 0.035 in. in dia. provided they are not grouped in a manner causing impairment

Outer Optical Area ..... maximum of 0.09 in. in dia. provided they are not grouped in a manner causing impairment

Non-visual and Optical Waived Areas ... visible defects within the 0.5 inch wide optics-waived area (area adjacent to mounting surface) shall be permitted regardless of size, provided it is structurally intact.

AIRCRAFT: A-7D/K TYPE: ATTACK (CLOSE AIR SUPPORT)
MANUFACTURER: LTV

TRANSPARENCY AND SUPPLIER	SHAPE	CROSS SECTION AND EDGE	MATERIALS
*WINDSHIELD			.125 ACRYLIC (CAST) .03 URETHANE .25 POLYCARBONATE .03 URETHANE .25 POLYCARBONATE .03 URETHANE .125 ACRYLIC (CAST)
CANOPY SWEDLOW			1875 STRETCHED ACRYLIC 25 NYLON EDGE

	SLOPE (DEGREES)
	WEIGHT (LB)
2598	DAYLIGHT AREA (IN.²)
	CABIN PRESSURE(PSI)
	MAX. CRUISE (KNOTS)
480	BIRD PROOF SPEED (KNOTS)
	RAIN REMOVAL (TYPE)
	HEATING

MISC. DATA:

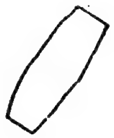
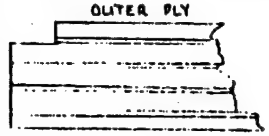
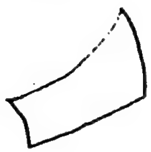
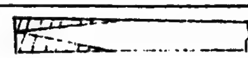
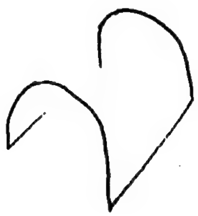
NEWER ONE PIECE WINDSHIELD WITH COMPOSITE AFT ARCH

* PROPOSED DESIGN

Figure 6. A-7D/K windscreen physical properties.

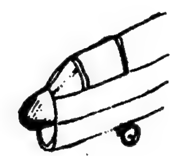
AIRCRAFT: A-7D **TYPE:** ATTACK (CLOSE AIR SUPPORT)

MANUFACTURER: LTY

TRANSPARENCY AND SUPPLIER	SHAPE	CROSS SECTION AND EDGE	MATERIALS
CENTER WINDSHIELD PPG		OUTER PLY  INNER PLY	.25 SEMI TEMPER .04 PVB .25 SEMI TEMPER .02 PVB .25 FULL TEMPER .02 PVB .25 FULL TEMPER .02 PVB .25 FULL TEMPER
SIDE WINDSHIELD SWEDLOW			.25 STRETCHED ACRYLIC .32 NYLON EDGE
CANOPY GLASS SWEDLOW			.1875 STRETCHED ACRYLIC .25 NYLON EDGE

SLOPE (DEGREES)			
WEIGHT (LB)	35	10 ea	48.2
DAYLIGHT AREA (IN.^{2})	259B	716	346
CABIN PRESSURE (PSI)			
MAX. CRUISE (KNOTS)			
BIRD PROOF SPEED (KNOTS)		[illegible]	
RAIN REMOVAL (TYPE)			
HEATING			

MISC. DATA:



(OLD VERSION)

Figure 7. A-7D windscreen physical properties.

A-10 Optical Parameters

ANGULAR DEVIATION

Quarter Panels ... Maximum of 6 min. of arc in all 4 zones

Center Panel ... Critical Vision Area - Maximum of 3 minutes of arc
Scanning Area - Maximum of 31.5 seconds of arc

OPTICAL DISTORTION

Quarter Panels ... Zone 1 - maximum of 1 grid per 10 grid run
Zone 2 - maximum of 1 grid per 8 grid run
Zone 3 - maximum of 1 grid per 4 grid run
Zone 4 - maximum of 1 grid per 2 grid run

Center Panel ... Critical Vision Area - Max. of 1 grid in 15
Scanning Area - Max. of 1 grid in 10

LUMINOUS TRANSMITTANCE

Quarter Panels ... Minimum of 83% measured perpendicular to the surface
Center Panel ... Minimum of 65% at a 52 degree angle of incidence

HAZE

Unavailable

OPTICAL DEFECTS

Any defect greater than the maximum diameter for minor optical defects and any chips or cracks that would cause structural problems

MINOR OPTICAL DEFECTS

Bubbles - Minor defect if between 0.062 and 0.15 inches

Lint - Minor defect if between 0.062 and 0.15 inches

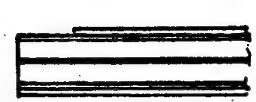
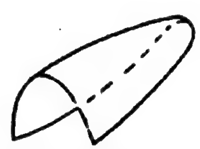
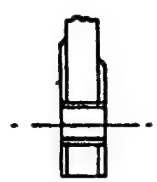
Pits - Minor defect if between 0.062 and 0.25 inches

Bullseye - Minor defect if between 0.062 and 0.25 inches

Foreign Objects - Minor defect if between 0.062 and 0.125 inches

AIRCRAFT: A-10A TYPE: ATTACK (CLOSE AIR SUPPORT)

MANUFACTURER: FAIRCHILD REPUBLIC CO.

TRANSPARENCY AND SUPPLIER	SHAPE	CROSS SECTION AND EDGE	MATERIALS
WINDSHIELD CTR. PANEL PPG TRIPLEX	 FLAT	 OUTBD	GLASS LAMINATE (SODA LIME) .187 SEMI-TEMPER .080 PVB INTERLAYER .375 FULL TEMPER .040 PVB INTERLAYER .375 FULL TEMPER .080 PVB INTERLAYER .125 LIGHT TEMPER
SIDE PANEL PPG GOODYEAR	 COMPOUND CURVED	 OUTBD	PLASTIC LAMINATE .080 CAST ACRYLIC .030 POLYURE. INTER. .156 POLYCARBONATE .030 POLYURE. INTER. .156 POLYCARBONATE .030 POLYURE. INTER. .080 CAST ACRYLIC RUBBER BUSHED ALUM. SPACER
CANOPY SWEDLOW	 COMPOUND CURVED	 OUTBD	MONOLITHIC ACRYLIC .06 NYLON FABRIC .25 STR ACRYLIC .06 NYLON FABRIC ALUM. SPACER

Windshield	Side panel	Canopy	Property
38° @ ℄ ACFT			SLOPE (DEGREES)
46.4	38.2 /SHIP SET	63	WEIGHT (LB)
2312	231 in.^{2}/PANEL	110	DAYLIGHT AREA (IN.^{2})
2.5			CABIN PRESSURE(PSI)
350			MAX. CRUISE (KNOTS)
-	300	300	BIRD PROOF SPEED (KNOTS)
-	-	JET AIR	RAIN REMOVAL (TYPE)
WINDSHIELD - CONDUCTIVE COAT. SIDE PANEL - HOT AIR (DEFOG) CANOPY - HOT AIR (DEFOG)			HEATING

MISC. DATA: DESIGN DRIVERS:
BIRD & BULLET IMPACT FOR W/S CTR PANEL.
BIRD IMPACT FOR W/S SIDE PANEL.

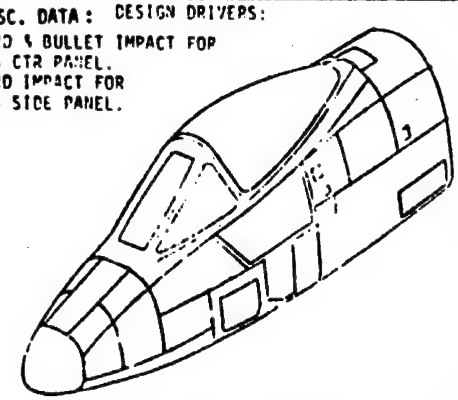


Figure 8. A-10A windscreen physical properties.

AV-8 Optical Parameters

ANGULAR DEVIATION

Windshield Only
Critical Vision Area ... maximum deviation of 1 minute of arc
Remaining Areas ... maximum deviation of 3.5 minutes of arc

OPTICAL DISTORTION

Windshield ... maximum allowable Grid Line Growth of 0.02 grid and there shall be no distortion which causes the observer to focus on the windscreen

Canopy ... maximum of 1.5 grids or a maximum of 2 grids is acceptable IF it is gradual (min. of 12 grid)

LUMINOUS TRANSMITTANCE ... Minimum of 89 %

HAZE ... AV-8/GR Mk.5/TAV-8 Windshield ... Maximum of 2 %
TAV-8 Blast Shield .... Maximum of 3 %

OPTICAL DEFECTS

Any optical defect which causes vision impairment shall be cause for rejection.

EXCEPTIONS:

Within 1 inch of any edging, adhesive burns or localized distortion at edge attachment joints or localized distortion resulting from rework of scratches or dings shall be disregarded unless it is objectionable to the inspector.

AV-8/GR Mk.5 ... Localized distortion within a 2 inch in diameter circle located on B.L. 0.000 and 17.25 inches from forward edge is acceptable

TAV-8 Forward Canopy ... Localized distortion within a 2 inch in diameter circle centered 18 inches, left or right, true along outer mold line from B.L. 0.000 and 24 inches from forward edge is acceptable

TAV-8 Aft Canopy ... Localized distortion within a 2 inch in diameter circle centered at the following locations (+) or (-) 1 inch is acceptable

-- 3 inches, left or right, true along outer mold line from 1.5 inches to the right of B.L. 0.000 and 4 inches from the forward edge measured at B.L. 0.000
-- On 1.5 inches to the right of B.L. 0.000 and 26.5 inches from the forward edge measured at B.L. 0.000
-- On 1.5 inches to the right of B.L. 0.000 and 35.5 inches from the forward edge measured at B.L. 0.000

B1-B Optical Parameters

ANGULAR DEVIATION

Zone 1 .... Maximum of 7 minutes of arc
Zone 2 .... Maximum of 10 minutes of arc
Zone 3 & 4 ... Not Applicable

OPTICAL DISTORTION

Zone 1 ... Maximum Grid Line Slope of 1 in 9
Zone 2 ... Maximum Grid Line Slope of 1 in 6
Zone 3 ... Maximum Grid Line Slope of 1 in 3
Zone 4 ... Not Applicable

LUMINOUS TRANSMITTANCE ... Minimum of 53 %

HAZE ... Maximum of 5 %

OPTICAL DEFECTS

Scratches

- ASTM F-428 Scratch Standards will be used to determine category
- Scratch Length refers to each individual scratch
- Scratches on the inner "heated" surface of the glass ply are acceptable if they are approximately parallel to current flow
- Faint hairline scratches are not accountable as optical defects

Scratch Category	Allowable Length in inches #4	#5	#6	#7
Zone 1	1.0	0.5	0.125	0
Zone 2	3.0	2.0	1.0	0
Zone 3	5.0	3.0	1.5	1.0
Zone 4	No scratches more severe than #7 No scratches greater than #6 shall extend to the edge of the glass			

MINOR OPTICAL DEFECTS

- Minor defects include: scratches, embedded particles, smears, pits, etc.
  Zone 1 ... Maximum number of 3 defects when visually inspected
  Zone 2 ... Maximum number of 5 defects when visually inspected
  Zone 3 ... Maximum number of 5 defects when visually inspected

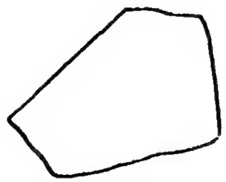
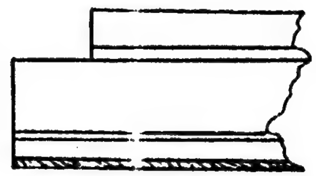
- The area of a defect shall not exceed 1/64 square inches, defects less than 0.05 in. in dia. are acceptable provided they are not grouped in a manner causing impairment

- Cuts 0.005 inches in depth or greater shall be cause for rejection

- No more than 2 defects shall occur in a circular area 12 inches in dia.

AIRCRAFT: B-1B **TYPE:** BOMBER

MANUFACTURER: ROCKWELL

TRANSPARENCY AND SUPPLIER	SHAPE	CROSS SECTION AND EDGE	MATERIALS
WINDSHIELD			.12 TEMPERED GLASS .235 SILICONE INTERLAYER .87 POLYCARBONATE .120 SILICONE INTERLAYER .15 POLYCARBONATE PROTECTIVE COATING

SLOPE (DEGREES)	
WEIGHT (LB)	
DAYLIGHT AREA (IN.^{2})	
CABIN PRESSURE(PSI)	
MAX. CRUISE (KNOTS)	
BIRD PROOF SPEED (KNOTS)	550
RAIN REMOVAL (TYPE)	
HEATING	

MISC. DATA:

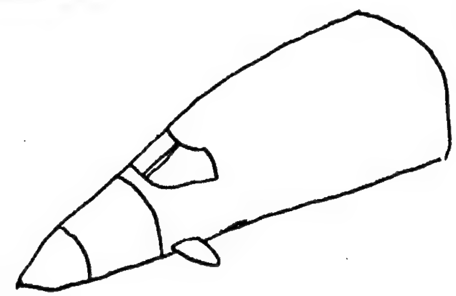


Figure 9. B-1B windscreen physical properties.

F-5E Windshield Optical Parameters

ANGULAR DEVIATION

Flight Area - maximum of 1.4 grids determined from pilot's eye position

Gunsight Area - maximum of 1 grid determined from pilot's eye position

OPTICAL DISTORTION

Flight Area and Gunsight Area - any apparent grid line shall not exceed 1/2 in any 2 x 2 square (4 grids)

And shall not exceed a gradual change of 1.2 inches in 12 inches of run

LUMINOUS TRANSMITTANCE

In Accordance With MIL-P-25690A

HAZE

Maximum of 3% for unweathered monolithic acrylic (IAW MIL-P-25690A)

MINOR OPTICAL DEFECTS

Flight Area - Maximum of 1 minor defect per 1 foot squared circular area (template radius is 6.77 inches)
No Major defects are permitted

Gunsight Area - No Major or Minor defects shall be permitted

- Minor defects are considered to be embedded particles, bubbles, dimples, etc. that do not exceed a 0.125 inches in diameter, or scratches that do not exceed 0.005 inches in depth

- Major defects are chips, cracks, spalls, gouges, and scratches deeper than 0.005 inch and more than 0.05 inch in length or other defects clustered to produce sustained visual distraction

F-5E and F-5A Crew Enclosures Optical Parameters

ANGULAR DEVIATION

Windshield ... Supercritical Area - maximum of 0.3 grid
Critical Area - maximum of 0.4 grid

Canopy ... Critical Area - maximum of 0.5 grid

OPTICAL DISTORTION

Windshield ... Supercritical Area - Maximum apparent grid line slope of 1/5 in any 2 x 2 square (4 grids) and Maximum of 0.4 inch in 6 inches of run

Critical Area - Maximum of 0.5 grid in 6 grids of run

Canopy ... Critical Area - Maximum apparent grid line slope of 1/3 in any 2 x 2 square (4 grids) and Maximum of 0.5 inch in 4 inches of run

LUMINOUS TRANSMITTANCE - In Accordance With MIL-P-25690A

HAZE - Maximum of 3% for unweathered monolithic acrylic (IAW MIL-P-25690A)

MAJOR OPTICAL DEFECTS

Windshield ... Supercritical and Critical Areas - No major defects allowed
Noncritical Area - Acceptable provided no structural weakening

Canopy ... Critical Area - No major defects are allowed
Semi-Critical Area - Major defects are not allowed
Noncritical Area - Acceptable provided no structural weakening

MINOR OPTICAL DEFECTS

Windshield ... Supercritical Area - No defects are allowed
Critical Area - Maximum of 1 minor defect per 1 foot squared of circular area (template radius is 6.77 inches)
Noncritical Area - Acceptable provided no structural weakening

Canopy ... Critical Area - Maximum of 2 minor defects provided that 2 or more defects cannot be encompassed in 1 foot squared of circular area
Semi-Critical Area - Maximum of 1 minor defect provided that 2 or more defects cannot be encompassed in 1 foot squared of circular area
Noncritical Area - Acceptable provided no structural weakening

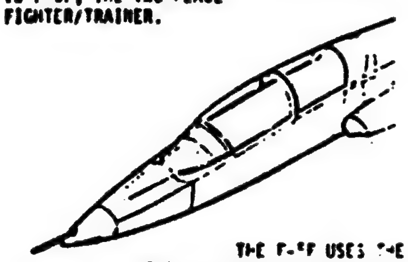
AIRCRAFT: F-5 TYPE: FIGHTER

MANUFACTURER: NORTHROP CORP.

TRANSPARENCY AND SUPPLIER	SHAPE	CROSS SECTION AND EDGE	MATERIALS
WINDSHIELD SIERRACIN PPG	 CURVED CONICAL		.71 STR. ACRYLIC MIL-P-25690 FIBERGLASS EDGE
CANOPY PPG	 COMPOUND CURVED	END  SIDE 	.25 STR SCRYLIC MIL-P-25690

24° ? ∡		SLOPE (DEGREES)
31	42	WEIGHT (LB)
1200	680	DAYLIGHT AREA (IN.^{2})
5 PSI		CABIN PRESSURE
Mach 1.6		MAX. CRUISE (KNOTS)
≈120	≈260	BIRD PROOF SPEED (KNOTS)
NONE		RAIN REMOVAL (TYPE)
HOT AIR DEFOG		HEATING

MISC. DATA: F-5E IS SINGLE PLACE, SHOWN HERE IS F-5F, THE TWO-PLACE FIGHTER/TRAINER.



THE F-5F USES THE SAME TRANSPARENT PARTS SHOWN FOR THE T-38.

Figure 10. F-5 windscreen physical properties.

F-14A Tomcat Optical Parameters

ANGULAR DEVIATION

Unavailable

OPTICAL DISTORTION

Zone 1 ... maximum of 1 grid per 12 grid run
Zone 2 ... maximum of 1 grid per 8 grid run

LUMINOUS TRANSMITTANCE

Unavailable

HAZE

Unavailable

OPTICAL DEFECTS

Rejectable Blemishes

Crazing is not permissible and crazed panels shall be rejected
Zone 1 .... Scratches over 0.01 inch deep are rejectable
Zone 2 and 3 ... Scratches over 0.01 inch deep are subject to Material Review Board action

MINOR OPTICAL DEFECTS

Minor defects are blemishes such as pinholes, pimples, cement marks, orange peel, hazing, and similar defects which do not impair transparency or reduce visibility and are not grouped in a manner that creates the effect of a major blemish.

Zone 1 ... maximum of 1 minor defect per 1 square foot of circular area
Zone 2 ... maximum of 2 minor defect per 1 square foot of circular area
Zone 3 ... minor defects in excess of 2 are not cause for rejection

NOTE: A cluster of no more that 3 blemishes within a 1 inch diameter circle can be considered one blemish. However, any such cluster in Zone 1 and 2 shall be at least 3 inches from another cluster or blemish within a 1 square foot circular area.

AIRCRAFT: F-14A TOMCAT TYPE: INTERCEPTOR/FIGHTER

MANUFACTURER: GRUMMAN AEROSPACE

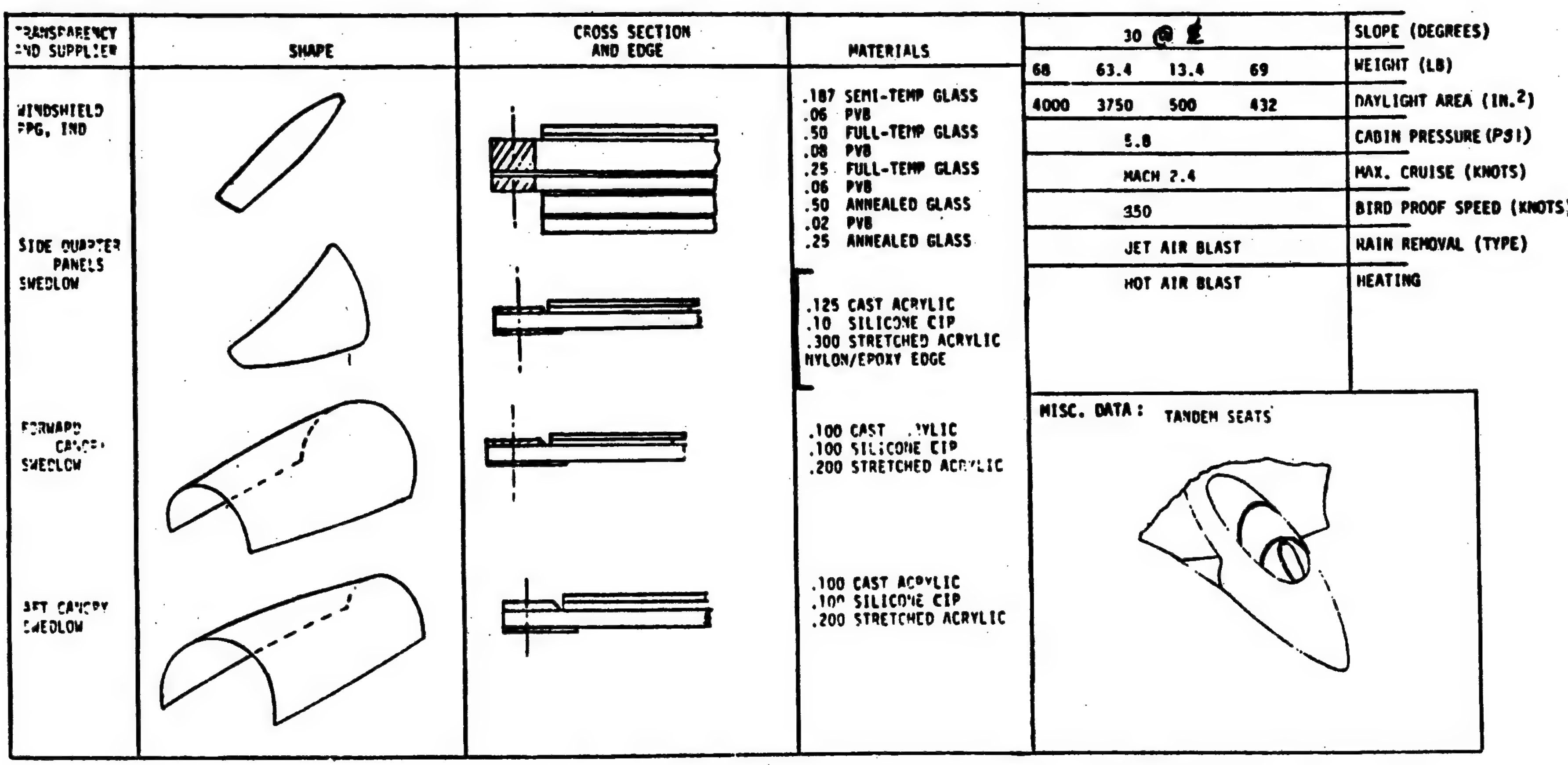


Figure 11. F-14A windscreen physical properties.

F-15 Optical Parameters

ANGULAR DEVIATION

Critical Optical Area ... maximum of 1.8 minutes of arc (0.52 mrad)

Remaining Areas (except 1 inch from the trimmed edge of windshields without edging) ... maximum of 3.5 minutes of arc (1.02 mrad)

OPTICAL DISTORTION

Critical Optical Area for WINDSHIELD - Maximum allowable grid line growth on the photograph is 0.02 inch. Also, the area will be visually inspected for any distortion which makes the observer focus on the windshield.

FORWARD and AFT CANOPIES (single and two place aircraft only) - Shall be visually examined for distortion and Grid Lines shall generally appear parallel and shall indicate any abrupt changes

FORWARD CANOPY Supplement (single place aircraft only) - A photograph method shall be used with the photo enlarged to 12 squares (grid board squares) per inch. A displacement of 1 1/2 grids is acceptable. A displacement of 1 1/2 to 2 grids is acceptable if the change is gradual (occurring over a minimum of 12 grids)

LUMINOUS TRANSMITTANCE

Minimum of 89 %

HAZE

Maximum of 2 %

OPTICAL DEFECTS

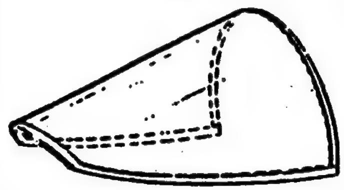
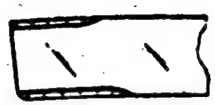
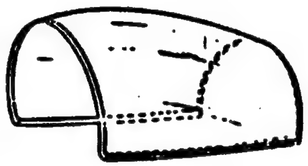
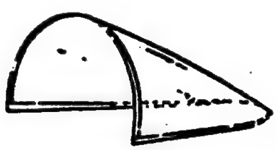
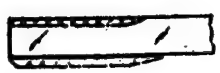
Any optical defect which causes vision impairment shall be cause for rejection.

EXCEPT: within 1 inch of any edging or any localized distortion caused by the reworking of scratches unless they are grouped together or are objectionable to the inspector

The transparency shall show no evidence of "orange peel" or "twinkling" which causes vision impairment

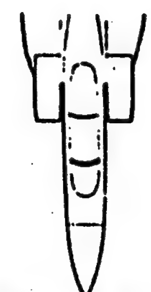
AIRCRAFT: F-15 TYPE: FIGHTER

MANUFACTURER: McDONNELL DOUGLAS

TRANSPARENCY AND SUPPLIER	SHAPE	CROSS SECTION AND EDGE	MATERIALS
WINDSHIELD (SWEDLOW)	 CURVED CONICAL		.90 STRETCHED ACRYLIC FIBERGLASS EDGE * .94 STRETCHED ACRYLIC
FWD CANOPY (SWEDLOW)	 COMPOUND CURVE		.30 STRETCHED ACRYLIC FIBERGLASS EDGE
AFT CANOPY (SWEDLOW)	 COMPOUND CURVED		.30 STRETCHED ACRYLIC FIBERGLASS EDGE

	28 @ ℄		SLOPE (DEGREES)
20	55	50	WEIGHT (LB)
1566	4300	1175	DAYLIGHT AREA (IN.^{2})
	5		CABIN PRESSURE(PSI)
	795 @ S.L.		MAX. CRUISE (KNOTS)
	394 PLUS *400 kts		BIRD PROOF SPEED (KNOTS)
	HOT AIR		RAIN REMOVAL (TYPE)
	HOT AIR		HEATING

MISC. DATA:



* FOR THE E-MODEL IN PRODUCTION NOT BOLTED TO FRAME

Figure 12. F-15 windscreen physical properties.

F-16 A/B/C/D Optical Parameters

ANGULAR DEVIATION

The method used to correct for angular deviation in the F-16 is a unique approach to limiting visual error caused by the canopy. The aircraft's onboard computer is used to correct for the angular deviation in the windscreen. When the pilot positions the pipper on a target, the computer adjusts for the angular deviation error in order to accurately deliver the weapon to the true target. The methods and the correction formulas that are used are too lengthy to include here, but for further information, refer to AFAMRL-TR-82-8, "The Measurement of Angular Deviation and its Relation to Weapons Sighting Accuracy in F-16 Canopies".

Binocular Disparity limits are set for the azimuth of F-16 C/D only. The area to be measured is 6 degrees right and left of center in azimuth and from 2 degrees to 12 degrees down in elevation. Limits are:

- 42 values shall not exceed -4.0MR to +4.0MR
- 41 values shall not exceed -3.0MR to +2.5MR
- 42 values shall not exceed -2.5MR to +1.0MR

OPTICAL DISTORTION

Visual Survey ... there shall be no apparent bending, blurring, divergence, convergence, or jumping of grid lines

Photographically Measured

Zone 1 ... Maximum of 1 grid per 11 grid run (except 1 in 9 in a limited forward area of Zone 1)
Zone 2 ... Maximum of 1 grid per 9 grid run

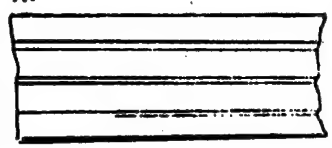
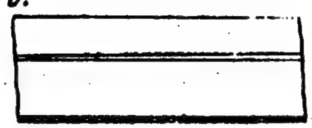
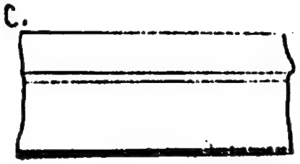
LUMINOUS TRANSMITTANCE ... Solar Coated - Minimum of 65 %
Non Solar Coated - Minimum of 79 %

HAZE ... Maximum of 4 %

MINOR OPTICAL DEFECTS

There shall be no more than 20 minor optical defects per zone (greater than 0.035 inches in diameter) as seen by the design eye position.

AIRCRAFT: F-16 TYPE: FIGHTER
MANUFACTURER: GENERAL DYNAMICS

TRANSPARENCY AND SUPPLIER	SHAPE	CROSS SECTION AND EDGE	MATERIALS
FOREWARD WINDSHIELD/ CANOPY			
GOODYEAR	see other data sheet for shape	A. 	.150 PLEX II ACRYLIC .030 POLYURETHANE .187 POLYCARBONATE .030 POLYURETHANE .187 POLYCARBONATE .030 POLYURETHANE .120 PLEX II ACRYLIC
TEXSTAR		B. 	.125 PLEX II ACRYLIC .06 POLYURETHANE .50 POLYCARBONATE COATING
SIERRACIN		C. 	.125 PLEX II ACRYLIC .03 SILICON .50 POLYCARBONATE COATING

SLOPE (DEGREES)	
WEIGHT (LB)	
DAYLIGHT AREA (IN.^{2})	
CABIN PRESSURE (PSI)	
MAX. CRUISE (KNOTS)	
BIRD PROOF SPEED (KNOTS)	
RAIN REMOVAL (TYPE)	
HEATING	

MISC. DATA:

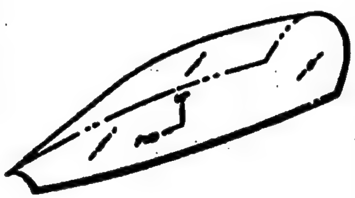
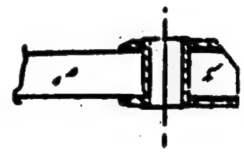
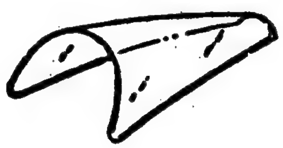
A. IN SERVICE BUT NOT IN PRODUCTION

B., C. THESE LAMINATED CANOPIES ARE IN PRODUCTION

Figure 13. F-16 windscreen physical properties.

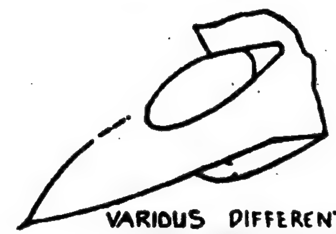
AIRCRAFT: F-16 TYPE: FIGHTER

MANUFACTURER: GENERAL DYNAMICS

TRANSPARENCY AND SUPPLIER	SHAPE	CROSS SECTION AND EDGE	MATERIALS
WINDSHIELD/ CANOPY (TEXSTAR)			* .75 POLYCARBONATE
AFT CANOPY (TEXSTAR)			.25 POLYCARBONATE

SLOPE (DEGREES)	12	31 AC C_L
WEIGHT (LB)	12	137
DAYLIGHT AREA (IN.^{2})	4200	
CABIN PRESSURE(PSI)	5	
MAX. CRUISE (KNOTS)	795 @ S.L.	
BIRD PROOF SPEED (KNOTS)	350 PLUS	
RAIN REMOVAL (TYPE)	GROUND APPLIED REPELLENT	
HEATING	NONE	

MISC. DATA: DESIGN DRIVEN BY VISION AND BIRD IMPACT.



VARIOUS DIFFERENT DESIGNS ARE CURRENTLY BEING EVALUATED. SEE NEXT DATA SHEET

*AN ACRYLIC - INTERLAYER - POLYCARBONATE LAMINATE IS BEING EVALUATED.

Figure 14. F-16 windscreen physical properties (continued).

F-18 Windshield Optical Parameters

ANGULAR DEVIATION

Critical and Center Optical Area ... maximum of 1 minute of arc
Outer Optical Area ... maximum of 2 minutes of arc
Remaining Vision Area ... maximum of 4 minutes of arc

OPTICAL DISTORTION

Optical Area ... Free of any distortion which causes the observer to focus on the windshield
Center Optical Area ... Maximum Grid Line Growth is 0.01 inches
Outer Optical Area ... Maximum Grid Line Growth is 0.02 inches

Canopy - visually inspected for grid lines that are generally parallel and indicate no abrupt slope changes

LUMINOUS TRANSMITTANCE ... Minimum of 89 %

HAZE ... Maximum of 2 %

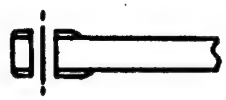
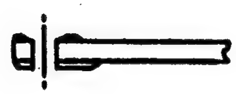
OPTICAL DEFECTS

- There shall be no defects that cause the observer to be distracted or to focus on the defect
- There shall be no evidence of surface or internal "Orange Peel" or "Twinkling", which cause visual impairment

MINOR OPTICAL DEFECTS

- If the diameter of defects exceeds 0.035 inches, it shall be cause for rejection, unless the defects do not cause vision impairment
- Defects less than 0.035 inches in dia. are acceptable, provided they are not grouped in a manner causing vision impairment
- Any defects (regardless of size) that cause visual impairment shall be cause for rejection
- Defects within 1 inch of any edging shall be disregarded unless they effect structural integrity

AIRCRAFT: F/A-18L TYPE: FIGHTER
(IDENTICAL TO F/A-18A OR TF-18A)
MANUFACTURER: NORTHROP/MCAIR

TRANSPARENCY AND SUPPLIER	SHAPE	CROSS SECTION AND EDGE	MATERIALS
WINDSHIELD SWEDLOW	 CURVED CONICAL		.05 FIBERGLASS EDGE .60 STRETCHED ACRYLIC .04 FIBERGLASS EDGE
CANOPY (SINGLE PLACE) SWEDLOW	 COMPOUND CURVED		.05 FIBERGLASS EDGE .25 STRETCHED ACRYLIC .08 FIBERGLASS EDGE
CANOPY (TWO PLACE) SWEDLOW	 COMPOUND CURVED TWO PIECES		.05 FIBERGLASS EDGE *.25 STRETCHED ACRYLIC .08 FIBERGLASS EDGE *.35 FOR FORWARD PIECE

24° @ A/C C_L			SLOPE (DEGREES)
106	49	47	WEIGHT (LB)
7300	3380	1500	DAYLIGHT AREA (IN.^{2})
5.5 PSI			CABIN PRESSURE
M2.0			MAX. CRUISE (KNOTS)
4 LB BIRD @ 360 KNOTS			BIRD PROOF SPEED (KNOTS)
JET AIR BLAST			RAIN REMOVAL (TYPE)
JET AIR BLAST			HEATING

MISC. DATA:

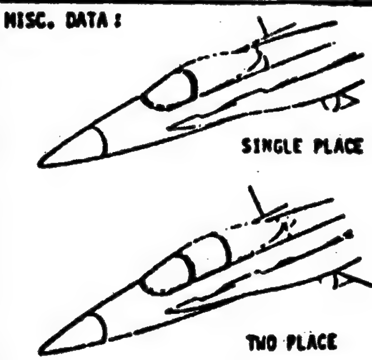


Figure 15. F/A-18L windscreen physical properties.

F-111 Optical Parameters

ANGULAR DEVIATION

Due to inadequacy in the previous deviation standards, the following revised standards were developed based on data collected from operational F-111 windscreens in May of 1982. The present revision requires that the avionics area be measured every 2 degrees and the non-avionics area be measured every 4 degrees. The reason the following error limits are set up in a statistical fashion is to fit the deviation error to a smooth curve across the windscreen, as well as to assign maximum limits for the allowable errors. This revision is subject to change as more data becomes available, but the theory should remain the same.

Avionics Area:	Maximum Allowed Value	
	Azimuth Error	Elevation Error
Absolute Value of the Mean	3.0 mrad	2.0 mrad
Standard Deviation	1.5	2.0
Absolute Maximum Value	7.0	5.0
Absolute Mean + Standard Deviation	4.0	3.0

Non-Avionics Area:	Maximum Allowed Value	
	Azimuth Error	Elevation Error
Absolute Value of the Mean	3.0 mrad	2.5 mrad
Standard Deviation	3.5	2.5
Absolute Maximum Value	9.0	6.0
Absolute Mean + Standard Deviation	3.0	5.0

OPTICAL DISTORTION

Windshield .. Unavailable

Canopies .... maximum of 1:10 in Zone 1
maximum of 1:6 in Zone 2

LUMINOUS TRANSMITTANCE

Windshield and Canopy
With Radar Reflective Coating - Minimum of 65 %
Without Radar Reflective Coating - Minimum of 84 %

HAZE

Windshield and Canopy
With Radar Reflective Coating - Maximum of 4 %
Without Radar Reflective Coating - Maximum of 3 %

OPTICAL DEFECTS

Scratches - 0.02 inch width, 0.01 inch depth or 3 inches in length

Lint or Hair - 3 inches in length

Smears or rubs - 5/8 inch wide or 1 1/2 inch length

Translucent Inclusions - 0.125 square inch area

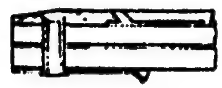
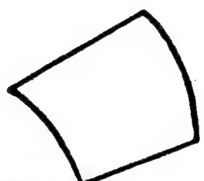
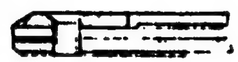
Opaque Inclusions - 0.07 square inch area

The total number of translucent inclusions between (0.35 - 0.125) or opaque inclusions between (0.35 -0.07) shall not exceed 12 per panel

Delaminated Areas
Outboard Acrylic Edge - max. of 1/8 inch around entire periphery
Inboard Acrylic Edge - max. of 1/4 inch around entire periphery

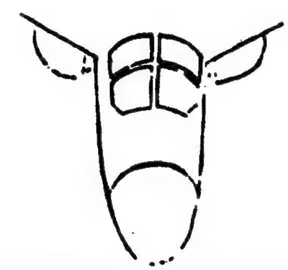
AIRCRAFT: F-111/FB-111 TYPE: FIGHTER/BOMBER

MANUFACTURER: GENERAL DYNAMICS

TRANSPARENCY AND SUPPLIER	SHAPE	CROSS SECTION AND EDGE	MATERIALS
WINDSHIELD (ADBIRT) SIERRACIN PPG SWEDLOW	 CURVED CONICAL		AL RETAINER .125 STR ACRYLIC .060 INTERLAYER .250 POLYCARBONATE .030 INTERLAYER .250 POLYCARBONATE SST STRAP
CANOPY (ADBIRT) SIERRACIN PPG SWEDLOW	 COMPOUND CURVED		AL RETAINER .125 STR ACRYLIC .060 INTERLAYER .125 POLYCARBONATE .030 INTERLAYER .125 POLYCARBONATE .020 NOMEX RETAINER

22° @ A/C ℄		SLOPE (DEGREES)
30	48	WEIGHT (LB)
1722	1767	DAYLIGHT AREA (IN.^{2})
9.2		CABIN PRESSURE
M2.5+		MAX. CRUISE (KNOTS)
500		BIRD PROOF SPEED (KNOTS)
JET AIR BLAST		RAIN REMOVAL (TYPE)
JET AIR BLAST		HEATING

MISC. DATA: DESIGN DRIVEN BY WEIGHT AND BIRD IMPACT.



NOTES: ADBIRT IS SECOND ITERATION OF F-111 TRANSPARENCY DESIGN. ORIGINAL WAS 2-PLY OF .12 GLASS; FIRST ITERATION (BIRT) IS HEAVY PLASTIC MULTIPLE CONSTRUCTION WITH A .25" THICK ACRYLIC OUTER PLY AND THREE .125 POLYCARBONATE PLIES.

Figure 16. F-111/FB-111 windscreen physical properties.

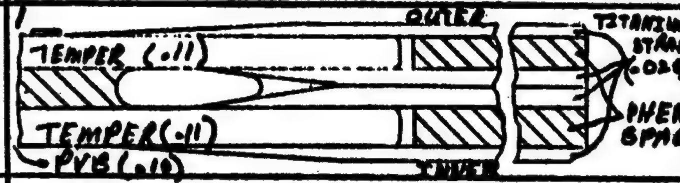
TRANSPARENCY WUC DRAWING NO.	MANUF. PART No.	BOLT-TYPE	CROSS – SECTION	AREA (IN²)	WEIGHT (lbs.)	TORQUE (lbs.-IN)
Front Windshield 16AAC/D 17-17683	PPG 17-17683	TITANIUM ALLOY		1714	39	20
Canopy Hatch 16ABD/E CK03200	PPG 17-17684	TITANIUM ALLOY	SEE DETAIL I SAME	1631	35	20

Figure 17. F/FB-111A/D/E/F windscreen physical properties (older configuration).

T-37 and A-37 Optical Parameters

ANGULAR DEVIATION

Unavailable

OPTICAL DISTORTION

Distortion Limits in Critical and Semicritical Areas

Separation Measurements (From Actual Photograph)	Max. Total Length of Split Lines
0 - 0.0115 inches	Unlimited
0.0115 - 0.02 inches	75 inches
0.02 - 0.03 inches	20 inches
0.03 - 0.04 inches	7 inches

LUMINOUS TRANSMITTANCE

Unavailable

HAZE

Any turbidity within the sheet or on the surface is allowable in the semicritical and not in the critical zone, provided it does not encompass more than one square inch, does not affect grid line definition, and does not affect overall quality of the part.

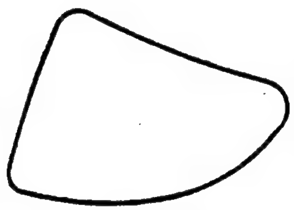
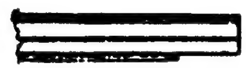
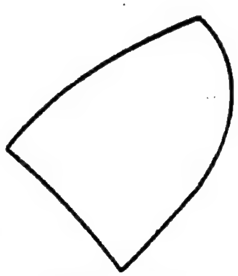
OPTICAL DEFECTS

Hairline Scratches - (not perceptible by fingernail test) - shall be less than 3 inches and not grouped together causing a fogged area

Fine cracks (crazing), fogged areas, loss of definition or blurred lines, or any condition that will be distracting to the pilot shall be cause for rejection.

AIRCRAFT: T-37B / A-37B TYPE: TRAINER / ATTACK

MANUFACTURER: CESSNA AIRCRAFT

TRANSPARENCY AND SUPPLIER	SHAPE	CROSS SECTION AND EDGE	MATERIALS
	 COMPOUND CONTOUR		.08 CAST ACRYLIC .03 INTERLAYER .19 POLYCARBONATE .03 INTERLAYER .19 POLYCARBONATE .03 INTERLAYER .08 POLYCARBONATE
	 COMPOUND CONTOUR		.250 STR ACRYLIC

SLOPE (DEGREES)	39 @ ℄ of AC	
WEIGHT (LB)	11.2	23
DAYLIGHT AREA (IN.^{2})	1038	893
CABIN PRESSURE(PSI)	NONE	
MAX. CRUISE (KNOTS)	T = 313	A = 440
BIRD PROOF SPEED (KNOTS)		250
RAIN REMOVAL (TYPE)	NONE	
HEATING	ANTI-ICE: NONE DEICING : HOT AIR	

MISC. DATA:

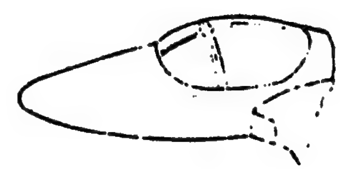


Figure 18. T/A-37B windscreen physical properties.

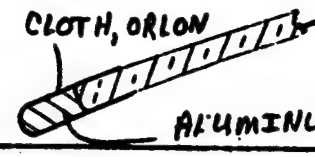
TRANSPARENCY WUC DRAWING NO.	MANUF. PART No.	BOLT-TYPE	CROSS-SECTION	AREA (IN²)	WEIGHT (lbs.)	TORQUE (lbs.-IN)
Windshield 111A/B 4011707	Goodyear 4011707	Low-Alloy Steel		893	NA	—
Canopy Glass 1112B 4011708	Goodyear 4011708	Low-Alloy Steel		1038	NA	—

Figure 19. T-37 windscreen physical properties (older configuration).

T-38 Optical Parameters

Student's Windshield (critical area)

ANGULAR DEVIATION

Determined from student's eye position ... maximum of 0.4 grid
Determined from instructor's eye position ... maximum of 0.7 grid
Except 6 inches wide across the forward edge ... maximum of 1 grid

OPTICAL DISTORTION

Determined from student's eye position ... maximum slope of 1/12
Determined from instructor's eye position ... maximum slope of 1/8

Student's Canopy (critical area)

ANGULAR DEVIATION

Determined from the instructor's eye position, deviation shall not exceed 1 grid forward, or 3 grids aft, of a line located 10 inches aft of the student's eye position

OPTICAL DISTORTION

Determined from instructor's eye position ... maximum slope of 1/8
EXCEPT: A slope of 1/5 is allowed, provided the total cumulative distorted area does not exceed 100 grids with no individual distortion area over 25 grids.

Instructor's Canopy (critical area)

ANGULAR DEVIATION

Rotate canopy's longitudinal centerline 60 degrees to the right and then rotate to the left of a perpendicular to the grid board ... from the instructor's eye the deviation shall not exceed 1 grid vertically and 0.8 grid horizontally

Raise canopy's longitudinal centerline 32 degrees from the horizontal and perpendicular to the grid board ... from instructor's eye the deviation shall not exceed 0.5 grid vertically and 0.8 grid horizontally within 50 grids to the right or left of the centerline

OPTICAL DISTORTION

From instructor's eye position ... maximum slope of 1/8

Instructor's Windshield (critical area)

ANGULAR DEVIATION

Determined from instructor's eye position ... maximum of 0.4 grid

OPTICAL DISTORTION

Determined from instructor's eye position ... maximum slope of 1/12

LUMINOUS TRANSMITTANCE

Minimum of 80% when measured normal to the surface

HAZE

Maximum of 3%

MINOR DEFECT

Embedded particles, seeds, bubbles, dimples, bumps that can be covered by a circle 0.25 inch in diameter or scratches up to 0.005 inches in depth. Also, minor defects are those which do not impair vision or are clustered to give the effect of a major defect.

MAJOR DEFECT

Cracks, chips, spalls, gouges or scratches in excess of 0.005 inch deep and 0.05 inch in length. Also, other defects clustered to produce a foggy area, cause distortion, or sustained visual distraction

ALLOWABLE DEFECTS FOR BOTH WINDSHIELDS AND CANOPIES

All Critical Areas (and Semi-critical Area for Instructors Canopy)

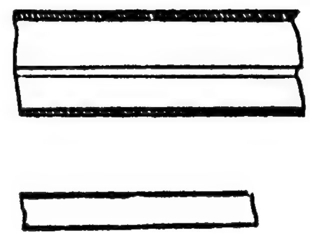
- No major defects allowed. Maximum of 1 minor defect per 1 square foot (6.77 inch radius) circular area

All Noncritical Areas

- Distortion and minor defects are acceptable, provided they do not weaken the structure or appear unsightly

AIRCRAFT: T-38 **TYPE:** TRAINER

MANUFACTURER: NORTHROP CORP

TRANSPARENCY AND SUPPLIER	SHAPE	CROSS SECTION AND EDGE	MATERIALS
WINDSHIELD PPG			PPG 5300 OUTER LINER .375 POLYCARBONATE .06 PPG 112 INTERLAYER .187 POLYCARBONATE PPG 8500 COATING
INSTRUCTORS WINDSHIELD SWEDLOW	SEE OLD CONFIGURATION FOR SHAPE		.50 POLYCARBONATE
CANOPY SWEDLOW	See OLD T-38 CONFIGURATION		

Property	Value
SLOPE (DEGREES)	
WEIGHT (LB)	
DAYLIGHT AREA (IN.^{2})	
CABIN PRESSURE(PSI)	
MAX. CRUISE (KNOTS)	
BIRD PROOF SPEED (KNOTS)	≈250 400
RAIN REMOVAL (TYPE)	
HEATING	

MISC. DATA:

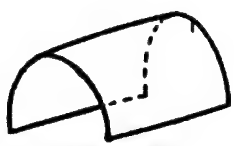
NEWER LAMINATED WINDSHIELD

USES SAME CANOPIES AS THE OLDER VERSION

Figure 20. T-38 windscreen physical properties.

AIRCRAFT: T-38 TYPE: TRAINER

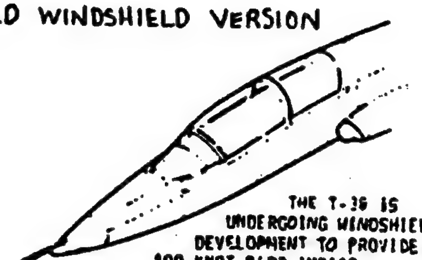
MANUFACTURER: NORTHROP CORP.

TRANSPARENCY AND SUPPLIER	SHAPE	CROSS SECTION AND EDGE	MATERIALS
FORWARD (STUDENT) WINDSHIELD SIERRANCIN PPG, IND.	 CURVED CONICAL		.60 STRETCHED ACRYLIC MIL-P-25690 FIBERGLASS EDGE ATTACH
AFT (INSTRUCTOR'S) WINDSHIELD SWEDLOW	 FLAT		.40 STR. ACRYLIC MIL-P-25690
FORWARD CANOPY SWEDLOW	 COMPOUND CURVED	END  SIDE 	.25 STRETCHED ACRYLIC MIL-P-25690 FIBERGLASS EDGE ATTACH
AFT CANOPY SWEDLOW	SIMILAR TO FORWARD CANOPY		.40 STRETCHED ACRYLIC MIL-P-25690

27°				SLOPE (DEGREES)
41	33	5.8	34	WEIGHT (LB)
1120	1490	280	550	DAYLIGHT AREA (IN.^{2})
5 PSI				CABIN PRESSURE
MACH 1.2				MAX. CRUISE (KNOTS)
120	120	≈80	220	BIRD PROOF SPEED (KNOTS)
NONE				RAIN REMOVAL (TYPE)
HOT AIR DEFOG				HEATING

MISC. DATA:

OLD WINDSHIELD VERSION



THE T-38 IS UNDERGOING WINDSHIELD DEVELOPMENT TO PROVIDE A 400 KNOT BIRD IMPACT CAPABILITY AND RETAIN THE THROUGH-THE-CANOPY (TTC) EJECTION CAPABILITY.

Figure 21. T-38 windscreen physical properties (older configuration).

The tables that follow are intended to show comparisons between the aforementioned aircraft. The three different Optical Parameters that will be addressed are:

Optical Parameter	Page Number
Maximum Allowable Haze	45
Minimum Allowable Luminous Transmittance	46
Maximum Allowable Distortion	47

The values for these charts were taken directly from the Specifications for each aircraft and then arranged in tabular form for clarity when comparing.

MAXIMUM ALLOWABLE HAZE CHART

AIRCRAFT	Haze Parameter
A-7	3.5 %
A-10	**
AV-8	
AV-8/GR Mk.5/TAV-8	2 %
TAV-8 Blast Shield	3 %
B1-B	5 %
F-5E Windshield	3 %
F-5E & F-5A Crew Enclosures	3 %
F-14A	**
F-15	2 %
F-16 A/B/C/D	4 %
F-18	2 %
F-111	
With radar reflective coating	4 %
Without radar reflective coating	3 %
T-37 & A-37	**
T-38	3 %

** Unavailable

MINIMUM ALLOWABLE LUMINOUS TRANSMITTANCE CHART

AIRCRAFT	Luminous Transmittance Parameter
A-7	79 % from pilot eye position
A-10	
Quarter Panels	83 % at normal
Center Panels	65 % at 52 degree incidence
AV-8	89 % normal to moldline
B1-B	53 % at normal
F-5E Windshield	IAW MIL-P-25690A
F-5E & F-5A Crew Enclosures	IAW MIL-P-25690A
F-14A	**
F-15	89 % normal to moldline
F-16 A/B/C/D	
Solar Coated	65 % at normal
Non-Solar Coated	79 % at normal
F-18	89 % normal to moldline
F-111	
With radar reflective coating	65 % at normal
Without radar reflective coating	84 % at normal
T-37 & A-37	**
T-38	80 % at normal

** Unavailable

MAXIMUM ALLOWABLE OPTICAL DISTORTION CHART

AIRCRAFT	OPTICAL DISTORTION
A-7	1:10
A-10	Quarter Panels - Zone 1 - 1:10 Zone 2 - 1:8 Zone 3 - 1:4 Zone 4 - 1:2 Center Panel - Critical Vision Area - 1:15 Scanning Area - 1:10
AV-8	Windshield - Max grid line growth of 0.02 Canopy - 1.5 grids per 12 grid run If gradual, 2 grids in 12 is acceptable
B1-B	Zone 1 - 1:9 Zone 2 - 1:6 Zone 3 - 1:3
F-5E Windscreen	Max. grid slope shall not exceed 1/2 in any 2 x 2 square and Max. of 1.2 in 12 grids of run
F-5E & F-5A Crew Enclosures	WINDSHIELD - Supercritical Area - Max. grid line slope of 1/5 in any 2 x 2 square and Maximum of 0.4 in 6 grids of run Critical Area - Max. of 0.5 in 6 grids of run CANOPY - Max. grid line slope of 1/3 in any 2 x 2 square and Max. of 0.5 in 4 grids of run
F-14A	Zone 1 - 1:12 Zone 2 - 1:8
F-15	Max. grid line growth of 0.02
F-16 A/B/C/D	Zone 1 - 1:11 (except 1:9 in small forward area) Zone 2 - 1:9
F-18	Center Optical Area - Max. grid line growth of 0.01 Outer Optical Area - Max. grid line growth of 0.02
F-111	Windscreen - Unavailable Canopy - Zone 1 - 1:10 Zone 2 - 1:6

OPTICAL DISTORTION CHART (Continued)

T-37 & A-37

Limits in Critical and Semicritical Area

Separation Measurement	Max. Total Length of Split Lines
0 - 0.0115	Unlimited
0.0115 - 0.02	75 inches
0.02 - 0.03	20 inches
0.03 - 0.04	7 inches

T-38 ... STUDENT WINDSHIELD - Student eye position - 1:12
Instructors eye position - 1:8

STUDENT CANOPY - 1:8 from instructors eye position (except 1:5 is allowed provided the total distorted area is accumulatively less than 100 grids with no individual distorted area over 25 grids

INSTRUCTOR WINDSHIELD - Instructors eye position - 1:12

INSTRUCTOR CANOPY - Instructors eye position - 1:8

CONCLUSION

This report reflects state of the art information that will obviously become outdated as technology continues to evolve. Revised editions of this Technical Report will be submitted whenever significant new information has accumulated. Hopefully, by reviewing the currently measured optical parameters in this report, the reader may now have a broader knowledge with which to apply the development of aircraft windscreens.

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AAMRL-TR-89-015

AN ILLUSTRATED GUIDE OF OPTICAL CHARACTERISTICS OF AIRCRAFT TRANSPARENCIES (U)

HAROLD S. MERKEL, CAPTAIN, USAF
HARRY L. TASK, Ph.D.

ARMSTRONG AEROSPACE MEDICAL RESEARCH LABORATORY

MARCH 1989

Final Report for February 1988– February 1989.

Approved for public release; distribution is unlimited.

ARMSTRONG AEROSPACE MEDICAL RESEARCH LABORATORY
HUMAN SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6573

NOTICES

TECHNICAL REVIEW AND APPROVAL

AAMRL-TR-89-015

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

CHARLES BATES, JR.
Director, Human Engineering Division
Armstrong Aerospace Medical Research Laboratory

REPORT DOCUMENTATION PAGE

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Merkel, Harold S., Capt, USAF; Task, H. Lee, Ph.D.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
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16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
01	03	
14	02	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

Windscreen, Windshield, Canopy, Haze, Disparity, Birefringence, Angular Deviation, Halation (Continued)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Aircraft transparencies are susceptible to numerous optical characteristics which may impact the visual performance of the aircrew. These characteristics range in severity from simply distracting to hazardous. This report describes and illustrates the ten most common of these optical characteristics. It may be used as a guide by aircrews, maintenance personnel, and others working with transparencies to assist them in accurately identifying transparency optical defects.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED
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Item 18 (Keywords) continued:

Multiple Imaging	Transparency	Rainbowing
Reflections	Aircraft	Crazing
Defect	Delamination	Characteristic
Optical	Diffraction	Polycarbonate
Distortion	Acrylic	

Preface

This report was prepared under work unit 7184-18-02 by members of Crew Systems Effectiveness Branch, Human Engineering Division, Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio. Funding was provided by the Wright Research and Development Center's Aircrew Protection Branch (WRDC/FIVR). The authors express their appreciation to Mr. Malcolm Kelley of FIVR for his careful review of the draft report.

This is the second of a series of three technical reports relating to aircraft transparencies. The first report, AAMRL-TR-88-058, entitled *Specifications and Measurement Procedures for Aircraft Transparencies*, was published in September of 1988. The third report, *Optical Terms and Definitions of Aircraft Transparencies*, has not yet been published. The inside front cover of this report contains instructions for obtaining copies of these reports.

Contents

List of Figures

Introduction

1.1 Purpose

The purpose of this report is to describe, and wherever possible illustrate, the optical characteristics common to aircraft transparencies. It may be used as a guide by aircrews, maintenance personnel, and others working with transparencies to accurately identify these characteristics.

It is important that windscreens which are removed from aircraft for optical deficiency are correctly labeled as to the nature of the deficiency and/or cause for removal. This information is used by Air Force laboratories to relate the severity of optical characteristics to aircrew acceptability. The results of these studies help the Air Force set realistic and relevant optical specifications for transparencies.

1.2 Background

The manufacturing of aircraft transparencies is not an exact process. Transparency manufacturers must control a number of variables in the production of a single transparency. One variable is the material from which transparencies are made. A sheet of polycarbonate, for example, might behave slightly differently than another sheet in the forming process, although both sheets are from the same supplier, and perhaps even from the same batch. Another variable is the process of finish polishing, which may be performed by an automated machine or in some cases by a skilled technician with a trained eye. These and other variables result in uncertainty in the optical quality of the final product.

Quality control of transparencies plays an important role in assuring that this variability in optical characteristics does not have a negative effect on the end user of the product, the

pilot. This is not easy because optical parameters are difficult to quantify in parameters which relate to visual performance. Furthermore, there is seldom a clear distinction between acceptable and unacceptable values for these parameters.

1.3 Scope

This document describes and illustrates some of the more common optical characteristics which may impact aircrew visual performance. It is not comprehensive in that it does not include characteristics other than of an optical nature. It also does not include obvious optical characteristics like large scratches and gouges from maintenance tools. These large scratches are a leading reason for transparency removals. Most of the information contained in this document will apply to aircraft transparencies in general; however, the intended application of this work involves primarily modern military aircraft.

1.4 Nomenclature

The aircraft transparency industry, like other specialized fields, has a unique vocabulary. Thus it is important to define some of the terms which are used to describe transparencies. Transparencies are typically categorized by three primary characteristics: location on the aircraft, structure of composition, and type of material.

Location: Transparencies categorized by location on the aircraft are known as windscreens, canopies, windows, or other specialized names. However, there are numerous aircraft designs, and not all windscreens will fit neatly into one of these categories.

A windscreen, also called a windshield, is a transparency located in the forward section of the cockpit and provides the primary area of vision for pilots. It is usually a single windscreen, or in a pair (left and right). The forward transparency on most general aviation, military, and commercial aircraft is called a windscreen.

A canopy is a transparency which provides vision mainly to the overhead and side areas. A canopy system commonly consists of a single canopy (F-15), two canopies in tandem (F-4, T-38), or two canopy hatches side by side (F-111). In many military and in some general aviation aircraft, there is only one transparency which covers the entire cockpit and provides vision to the forward as well as the side and overhead areas. In this case the entire transparency is referred to as the canopy. An example of this is the F-16.

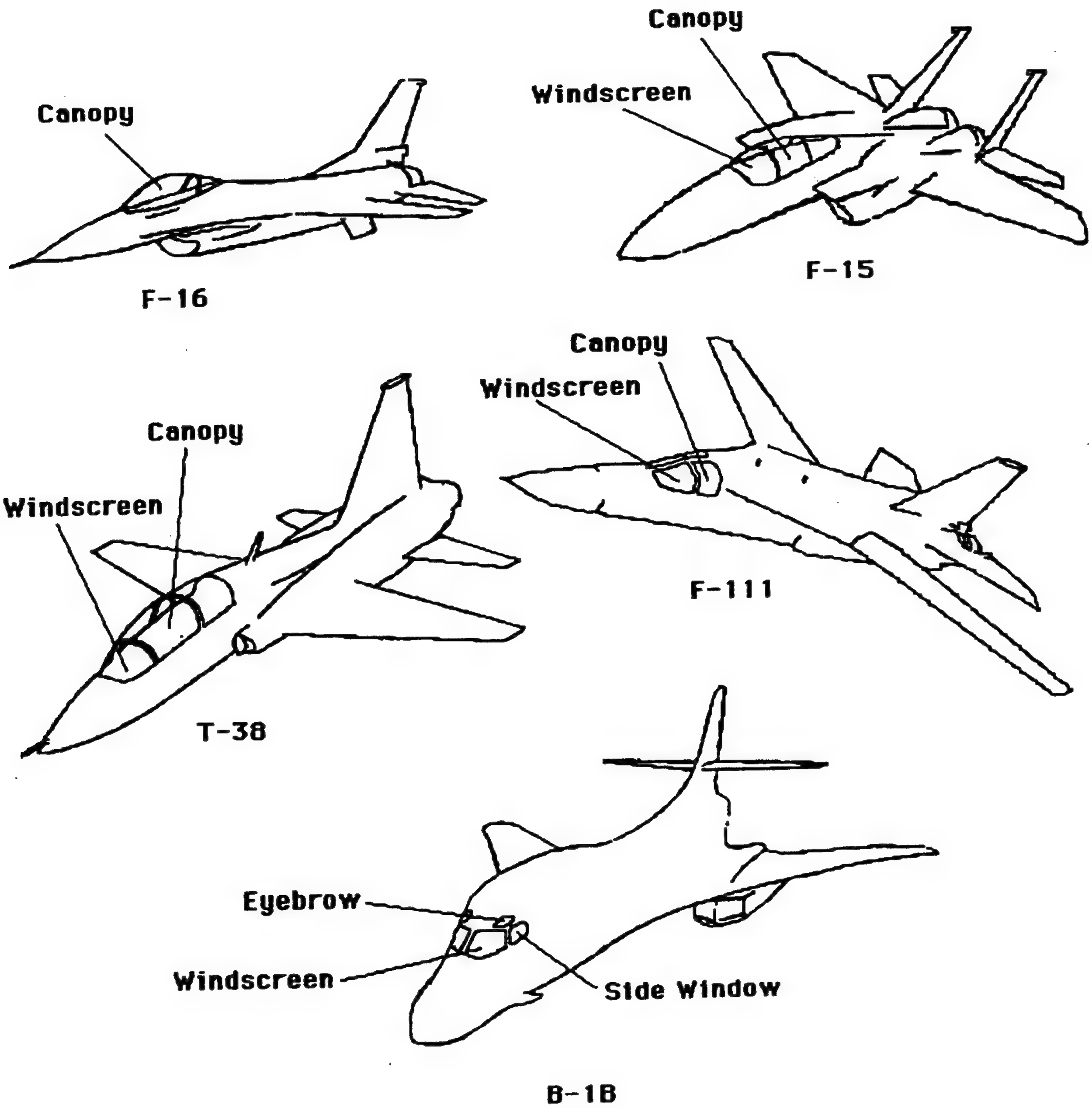

Figure 1.1: Some examples of aircraft transparencies.

A window is a transparency which provides vision mainly to the side areas. It is often smaller in size and can appear almost anywhere on the aircraft. Commercial passenger jets have many side windows, and most light general aviation aircraft have windows on the side door or fuselage.

Some other types of transparencies are the skylight and the eyebrow. Skylights are small overhead windows, often tinted, located above the pilot. The eyebrow is a small window found in pairs on some larger aircraft just aft of windscreen. The eyebrow windows provide limited vision to the forward overhead area. Figure 1.1 shows some examples of aircraft transparencies.

Composition: A transparency identified by structure of composition is known as either a monolithic or a laminate. A monolithic transparency is one which is constructed of a single ply of material. A laminate is a transparency which is constructed of two or more plies of material bonded together with another material known as an interlayer.

The plies of a laminated transparency may be of the same or different materials, and each ply has a specific name. The ply which provides primary strength of the transparency is known as the structural, main, or core ply, and is usually polycarbonate for smaller and faster aircraft (fighters) and glass for larger and slower aircraft (cargo aircraft). The ply exposed to the outer surface is commonly called the outer ply. It may be composed of glass, acrylic, or polycarbonate, and frequently has one or more coatings applied to it. The ply exposed to the inner surface is called the inner ply or spall shield. It is usually acrylic or polycarbonate, and may also have a coating applied to it (usually a hardcoat). Materials used to bond plies of a laminated transparency together are called interlayers; common interlayer materials are silicone and polyurethane. The interlayer is somewhat flexible to allow for thermal expansion of the plies while maintaining the bond between the plies.

Materials: Transparencies may also be identified by the type of material from which they are constructed. The most common materials are glass (includes various glass types), acrylic (cast and stretched), and polycarbonate. Laminates can be identified by a name such as a "polycarbonate/acrylic laminate". Materials are often identified by trade names within the transparency industry.

Glass is a very hard material and stands up well to abrasion, which makes it suitable for the outer surface of a windscreen, where many fine particles constantly impact the transparency during flight. The main disadvantages of glass are its weight and its inability

to withstand significant impacts.

Polycarbonate is a relatively flexible material. It is used for its light weight, strength and ability to withstand impacts. Its primary disadvantage is that its surface is relatively soft, so it is easily abraded and scratched.

Acrylic has qualities between those of glass and polycarbonate. Its surface hardness is greater than polycarbonate, making it more abrasion resistant, but less than that of glass. Its strength is greater than that of glass, but less than polycarbonate.

Descriptive names for transparencies can also be combined to be more specific. One might refer to a "monolithic stretched acrylic cabin window," or a "polycarbonate/glass laminate windscreen." These are just two of many possibilities.

Optical Characteristics

2.1 Format

This chapter contains a list of optical characteristics common to aircraft transparencies. The definitions and explanations that follow will be for terms as they apply and are related to aircraft transparencies. Some terms may have more general meanings or be defined differently in other fields. The format used for each characteristic is:

- *Name of characteristic:* (alternate names in parenthesis)
- *Explanation:* This section generally includes a brief definition; it may also include the reason for the characteristic or other significant information.
- *Inspection:* A brief statement of how to inspect an aircraft transparency for the particular characteristic.
- *Measurement:* A listing of the procedure used to measure (quantify) the characteristic, if a procedure exists. Many characteristics have no objective measurement procedure; only a subjective estimate of the severity is made. If a procedure has been established, it is often documented as an American Society for Testing and Materials (ASTM) Standard Method.
- *Visual effect:* A statement of the impact of the characteristic on aircrew visual performance.
- *Illustrations:* Since this document focuses on optical characteristics, a major part of it will be devoted to the photographs and illustrations.

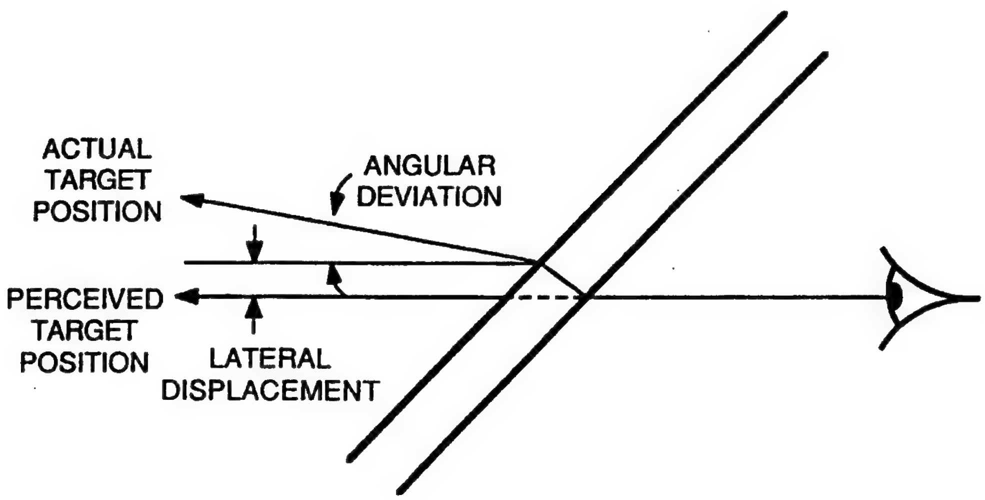

Figure 2.1: Angular Deviation.

2.2 Angular Deviation (prismatic deviation, deviation)

Explanation: Angular deviation is the angular change that occurs when a light ray passes through a transparency (see figure 2.1). The change is usually due to non-parallel surfaces in the transparency. The amount of angular deviation depends on the index of refraction of the material, the angle of incidence, and the shape of the material. (For a more detailed account refer to Hecht, 1975.)

It is especially important to characterize angular deviation in aircraft equipped with a head-up display (HUD). When the pilot places the HUD aiming reticle (pipper) on the target, he is aiming his weapon at the location where he visually perceives the target. If the transparency causes angular deviation, the target will actually be displaced from where the pilot sees it, similar to how an object under water appears in a different position from where it actually is.

Inspection: In general, angular deviation cannot be easily detected in the field by optical or visual means. Consistent bias effects in weapons aiming is an indication that uncompensated angular deviation may exist in the transparency. More often the derivative of angular deviation (rate of change of angular deviation) is noticed which manifests itself as distortion (see section on distortion).

Measurement: Measurement of angular deviation is performed with an angular deviation

device (ASTM Standard Method F801) or a collimated light source and theodolite. These measurements are done in a laboratory with the windscreen removed from the aircraft. At present there are no methods of measuring angular deviation in the field.

Visual Effect: There is no obvious visual effect of angular deviation; the only effect is an indirect one due to weapons system inaccuracies caused by the angular deviation as discussed above.

2.3 Binocular Disparity

Explanation: Binocular disparity exists when the image seen with the left eye is different from the image seen by the right eye. A certain amount of disparity is natural, since the eyes are physically separated. However, excessive binocular disparity may be caused by the transparency or the interaction of the transparency with the HUD, leading to visual problems.

Binocular disparity is most often caused by the binocular deviation of the transparency. Binocular deviation is the difference in angular deviation measurements made from the left and right eye positions for a given view angle. Thus it is the angle that the eyes would have to converge or diverge to fixate on an object located at optical infinity. Binocular disparity can also occur when the HUD symbology appears at a different optical distance than the outside target does. This can cause either the HUD symbology or the target to appear widened or double.

Inspection: Binocular disparity is sometimes difficult to notice by visual inspection. It may be detected by alternately closing the left and right eyes and observing a shift in the position of an object.

Measurement: Binocular deviation can be measured by taking angular deviation measurements from the left and right eye position and subtracting the left eye result from the right eye result. This is done for both horizontal and vertical angular deviation directions. The horizontal data provides information on eye convergence or divergence and the vertical data provides information on eye dipvergence (one eye having to rotate upward or downward compared to the other eye in order to fuse the images). It may also be quantified by taking double exposure photographs through the transparency, with one exposure made with the camera in the left eye position and the other from the right eye position (without

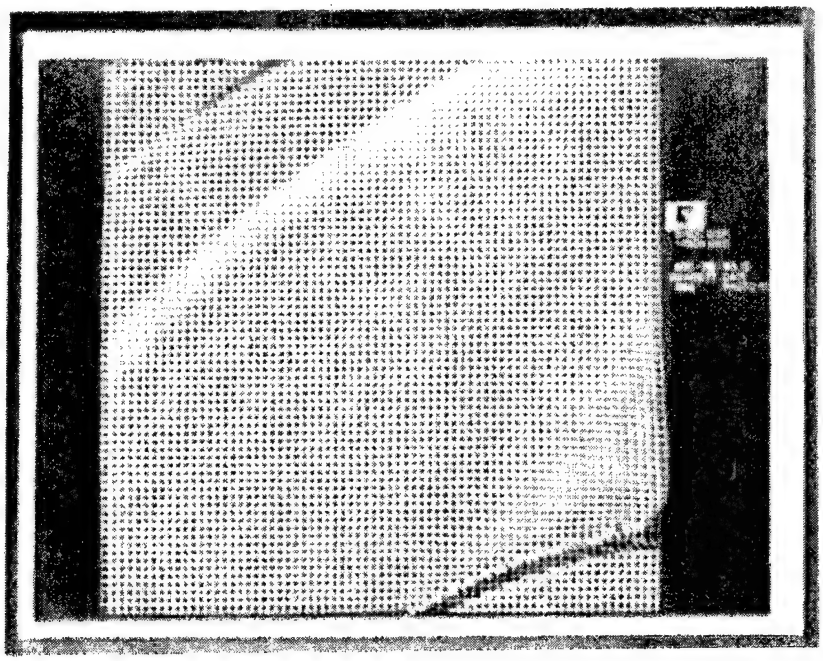

Figure 2.2: Double exposure photograph showing binocular deviation.

advancing the film). Separation of the grid lines indicates the presence of binocular deviation (see figure 2.2). This latter method, however, does not distinguish between lateral displacement effects and angular deviation effects. It is therefore only a good measure of binocular disparity for the specific grid board distance used to obtain the double exposure photographs.

Visual Effect: Binocular disparity may be manifested in several ways: eye strain, headache, fatigue, suppression of the image from one eye by the visual system, or doubling of vision. Sometimes these effects may occur only over a period of extended viewing. Tolerances for binocular disparity vary among individuals, so a certain amount of disparity may cause problems for one individual and not another.

2.4 Birefringence (rainbowing)

Explanation: The term birefringence means the material in question has two indices of refraction. Polycarbonate under stress becomes birefringent and thus exhibits two indices of refraction that align with the directions of the stress. These two indices of refraction cause polarized light to travel at different velocities through the material. The incoming linearly polarized light is converted to elliptically polarized light due to the birefringence. The degree of rotation of the electric field vector of the light further depends on the wavelength

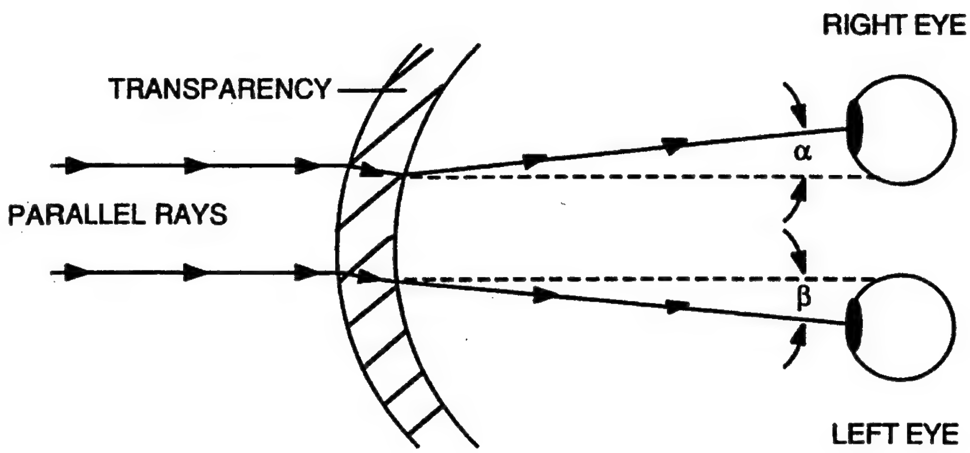

Figure 2.3: Binocular Deviation causing convergence of the eyes.

(color) of the light since the material also has a certain amount of chromatic dispersion. When the light exits the windscreen, the angle of exit acts like a partial analyzer (polarizer) which results in some wavelengths being attenuated more than others. Thus the exiting light exhibits a color effect depending on the degree of birefringence and the extent of the polarization. These color patterns, or rainbowing, can be relatively strong for clear blue sky days (blue sky can be about 80% polarized). The pattern of these colors on the windscreen remains constant as a result of built in residual stress in the windscreen (during the manufacturing process), but the actual colors making up the pattern will vary depending on the orientation of the windscreen with respect to the polarization vector of the exterior light.

Inspection: Birefringence is visible to the unaided eye when observing the transparency with a polarized light source, such as a clear blue sky. The birefringence pattern can be enhanced by observing it through a second polarizer, such as a pair of polarized sun glasses. (This is why USAF pilots are not allowed to fly with polarized sun glasses.)

Measurement: There is as yet no accepted method of measuring birefringence in terms of its effects on vision.

Visual Effect: Birefringence has been noted as a concern but has not been labeled as a problem. Anecdotal information gathered on F- 111 and B-1 windscreens indicates that the primary visual effect is one of annoyance or minor distraction.

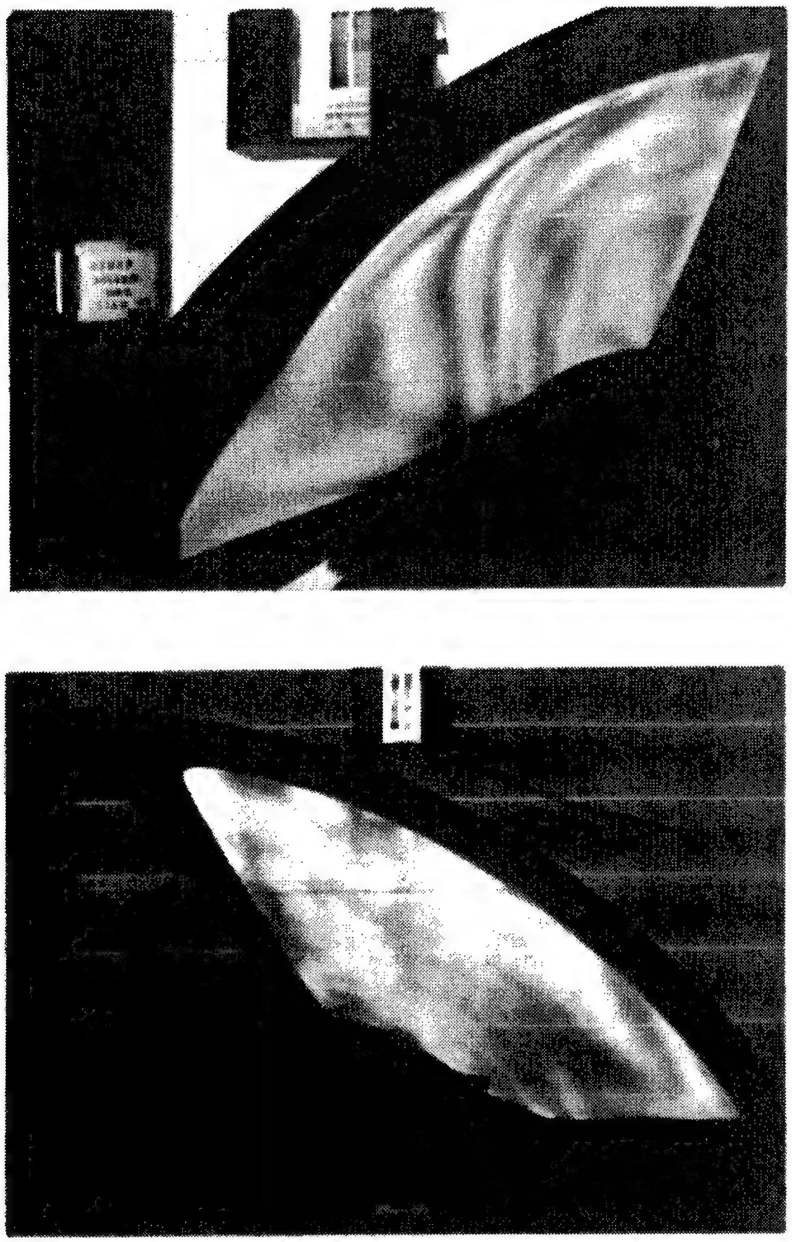

Figure 2.4: Birefringence patterns of F-111 windscreens produced by two different manufacturing techniques.

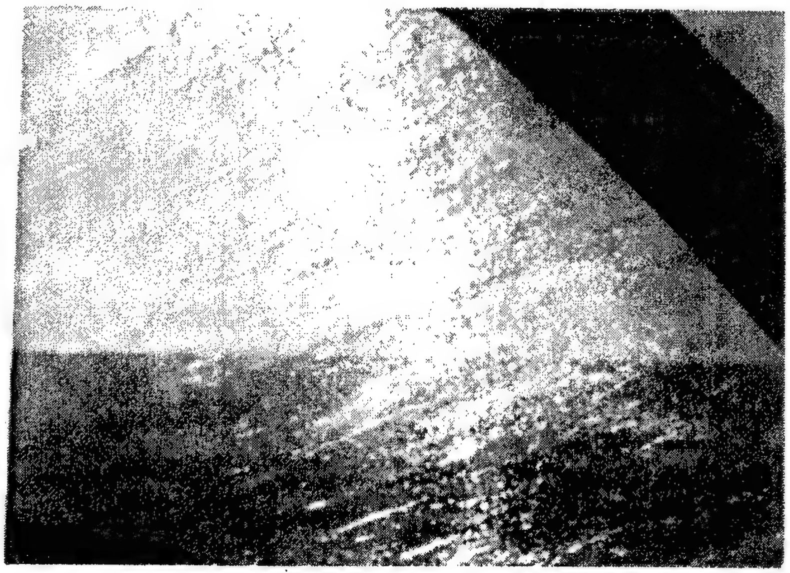

Figure 2.5: Example of crazing.

2.5 Crazing

Explanation: Crazing is the occurrence of very small "micro cracks" in a transparency or coating. These cracks usually are localized and are oriented in the same direction. In bright light conditions and at certain sun geometries, the cracks will act like many tiny mirrors and reflect light into the pilot's line of sight (see figure 2.5). Crazing may be induced by chemicals, age, or other causes.

Inspection: Visual examination of the transparency under bright light conditions is a good way to observe crazing. However, the appearance of crazing is dependent upon the relative positions of the light source, transparency, and observer, so it may be difficult to observe if the geometry is not right.

Measurement: There is no quantitative method to measure crazing as of this writing. Extent of crazing is left to subjective judgement.

Visual Effect: Crazing can be almost invisible and have essentially no effect on vision until the sun angle is just right and the micro-cracks (acting like little mirrors) reflect the sunlight directly into the pilot's eyes. Under this reflection condition the visual effect is significant loss of contrast in the exterior world scene which can cause severe visual impairment during the time the reflection geometry is satisfied.

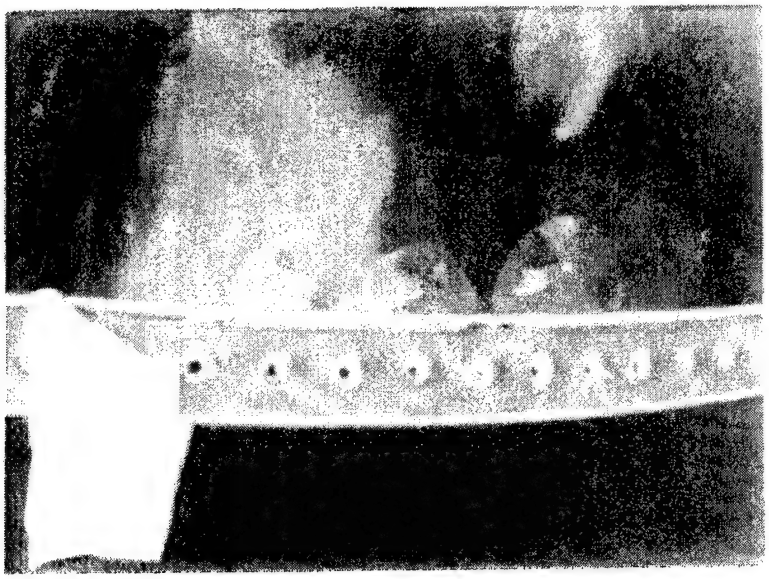

Figure 2.6: Delamination of an F-111 caused by overheating of the windscreen by the rain removal system.

2.6 Delamination

Explanation: Delamination is a separation of the layers of a laminated transparency which may be due to residual or induced stress in the transparency. There are several events that may enhance the occurrence of delamination, such as overheating the transparency, thermal cycling, and defective manufacturing.

Inspection: Delamination is detected by looking for bubble areas within the transparency; it often occurs near an edge.

Measurement: There is no specified method to measure delamination, although the width (distance from the edge of the windscreen) of the delamination area is commonly measured using a ruler.

Visual Effect: Delamination is easily noticed but is usually confined to the edges of a transparency (at least in its early stages). This reduces any effect on vision. The area that is delaminated has a lower transmissivity and higher reflectivity due to the extra air- plastic/glass interface that is created at the delamination. This also enhances the effect of multiple imaging.

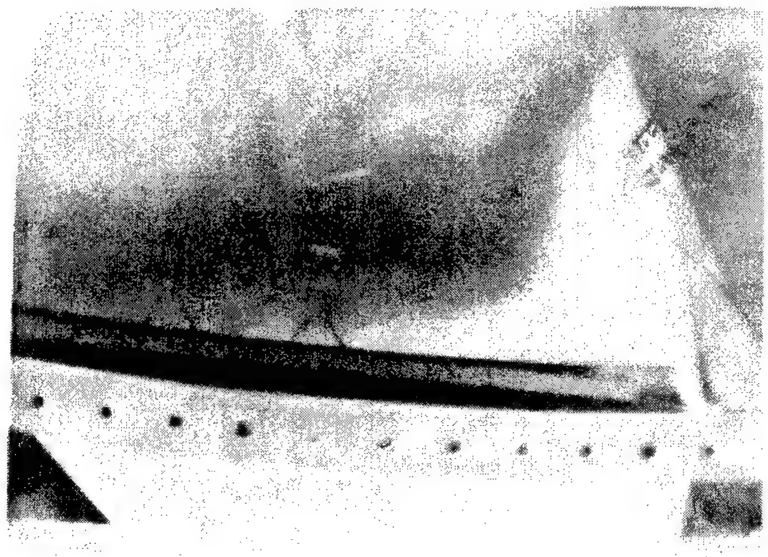

Figure 2.7: Delamination of a B-1B windscreen near the thermal sensors.

2.7 Diffraction (streaking, starburst patterns, bowtie effect, arcing)

Explanation: Diffraction is one of the three basic means by which light rays change their direction of travel (the other two are refraction and reflection). Diffraction is a rather complex subject, but the effect essentially occurs as a scattering of light from the edges of some obstacle. This scattering can occur from objects too small to see or from easily visible scratches on the surface of a transparency. Diffraction of light from very tiny objects (at the molecular level) is what gives rise to haze. This type of effect is evident in even new materials since it is a characteristic of the material itself (haze or halation is discussed in section 2.9). Diffraction also occurs from inclusions (meshes) and microscratches on the surface of the windscreen. Sometimes these scratches are not in random orientations but are in uniform directions, which give rise to an easily noticeable diffraction pattern. If the scratches are all in one direction or arch, the resulting diffraction pattern will appear as streaks emanating from point sources of light. These patterns are usually only evident at night when viewing point sources of light. This is because in the daytime the daylight scene washes out the pattern effects making them invisible to the naked eye.

Inspection: Diffraction is detected by looking through the transparency at a light source at night or in a dark environment.

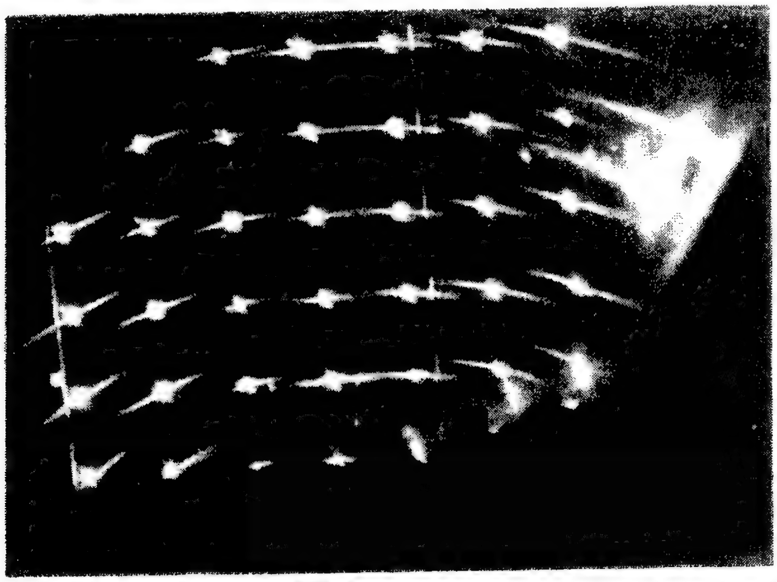

Figure 2.8: Diffraction patterns of the lights of a multiple imaging light array as viewed through a defective B-1B windscreen.

Measurement: There is no measurement for diffraction other than a subjective assessment.

Visual Effect: Diffraction patterns are usually only distracting; they are observed primarily at night.

2.8 Distortion

Explanation: Distortion is the rate of change of angular deviation across the transparency. It can be caused by non-parallelisms in the surfaces of a transparency or localized changes in the index of refraction of the transparent material. There are several types of distortion which have specific names within the transparency industry. Some of the more common types are listed here:

1. *bullseye* – caused by a localized depression or bulge in the transparency, creating a circular lens-like distortion; hence, the name "bullseye."

2. *band distortion* – distortion occurring in a narrow, elongated region across an area of the transparency.

3. *edge distortion* – distortion occurring at or near the edge of a transparency. Often the most severe distortion within the transparency will occur along an edge.

4. *deletion line distortion* – a thermally induced distortion occurring around the heater

Figure 2.9: Diffraction of a point light source through a canopy.

coating deletion line. A large temperature gradient between the heated and unheated portions of the windscreen may cause localized distortion in some transparencies where the index of refraction varies with temperature.

Inspection: Distortion is readily identified visually by viewing objects through the transparency and noting waviness in lines and changes in the shapes and relative sizes of objects, particularly near the edges of a transparency and in areas where the viewing angle is very acute.

Measurement: Currently three methods for measuring distortion are used within the transparency industry: grid line slope, displacement grade, and lens factor. The most widely used method is grid line slope (ASTM Standard Method F 733 or variations). Grid line slope measurements are made by taking a photograph of a grid board through the windscreen. The maximum slope of a horizontal grid line is the grid line slope value of the transparency.

Visual Effect: The visual effects of distortion depend upon the severity of distortion. Distortion may be distracting, give false motion cues by changing the perceived relative velocity of out-of-the-cockpit objects, or in some cases cause headache and nausea. Minor distortions, while aesthetically unappealing, have shown no significant degradation on the performance of visual tasks.

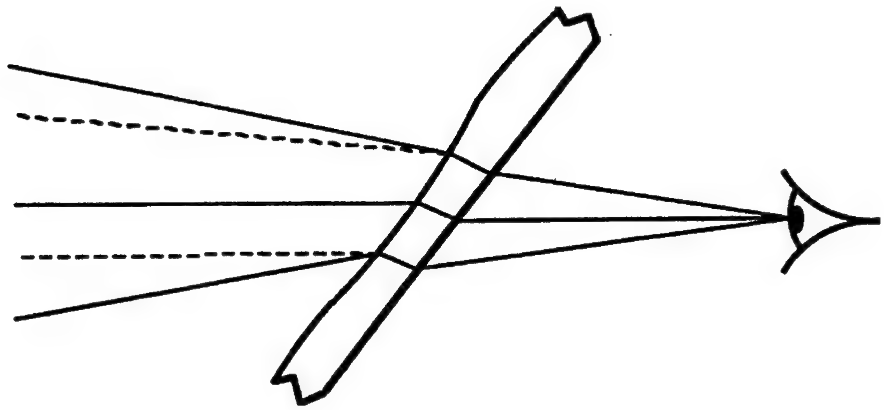

Figure 2.10: An illustration of how distortion occurs.

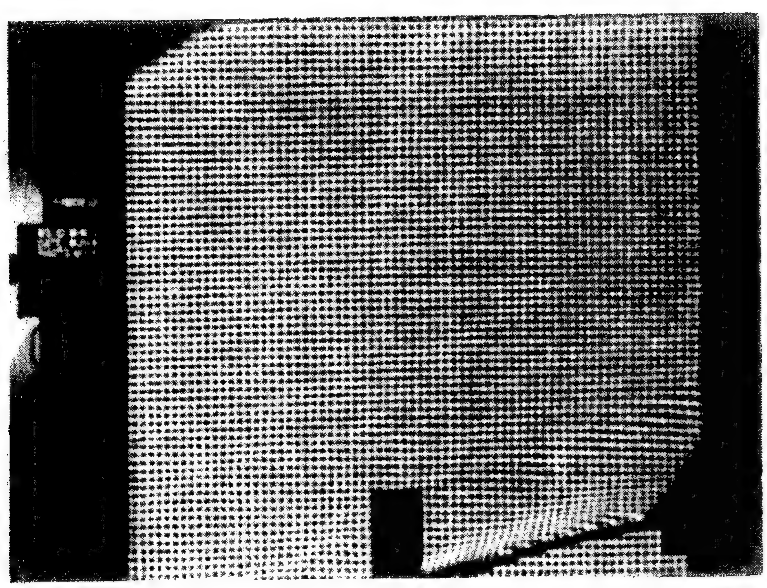

Figure 2.11: Distortion of a grid board as viewed through a transparency.

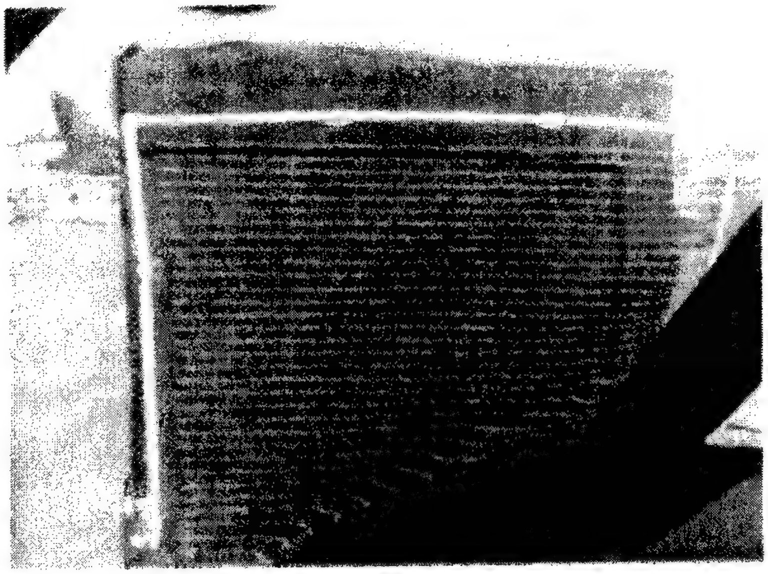

Figure 2.12: Distortion of a field-portable string board through a B-1B windscreen. Note the edge distortion.

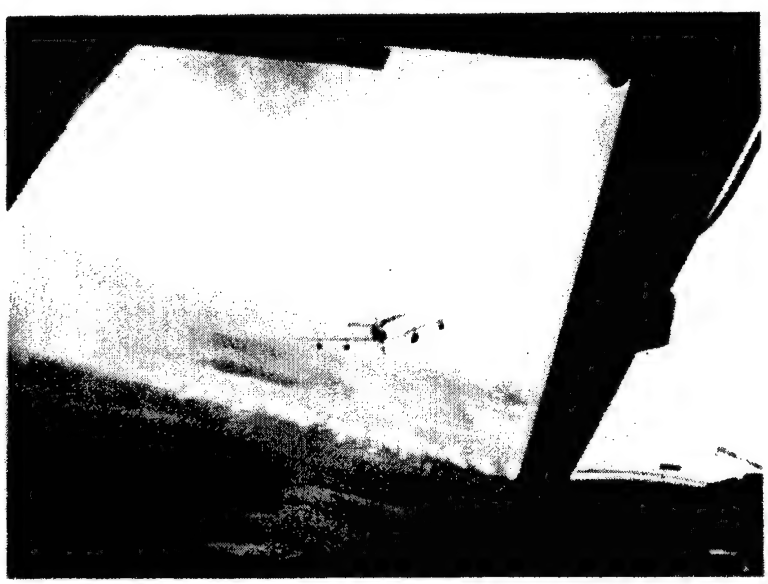

Figure 2.13: Distortion of an aircraft when viewed through the heater coating deletion line of a B-1B windscreen.

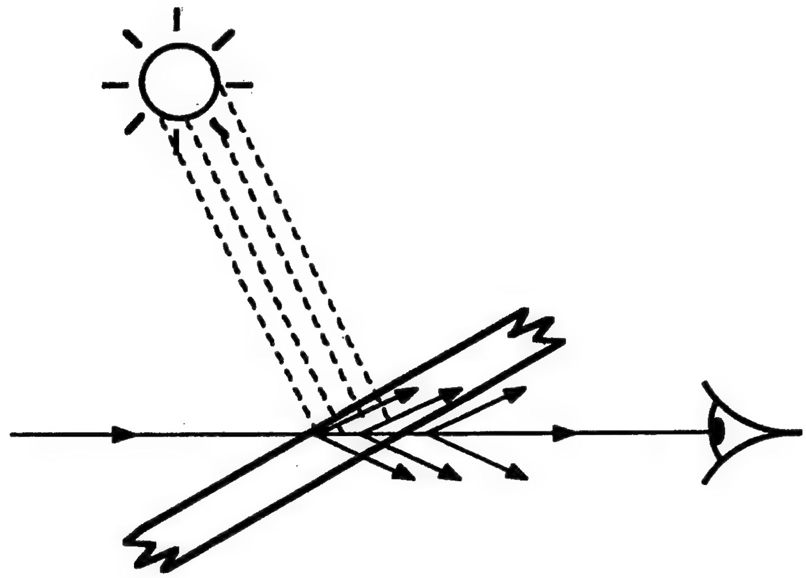

Figure 2.14: An illustration of how halation occurs.

2.9 Halation (haze, scatter, glare)

Explanation: Halation is the scattering of light by the windscreen into the line of sight of the pilot. It is caused by the diffraction of light by particles within the transparency or by fine scratches and/or dirt on the surface. It is most significant when flying towards the sun and may occlude significant portions of the field of view. (See figures 2.14 and 2.15.)

Inspection: Halation is observed by looking through the transparency with a bright light source (or the sun) shining on it. Any veiling glare or scattered light by the transparency that interferes with your view is known as halation, or haze. The amount of haze depends on the intensity and location of the light source and the view angle.

Measurement: Halation may be measured by ASTM Standard Method F 943 in the field and in the laboratory or by D 1003 in the laboratory only. Haze may be quantified as the haze index value (by ASTM F 943) or as percent haze (ASTM D 1003).

Visual Effect: Halation reduces the contrast of objects viewed through the transparency, which makes out-of-the-cockpit objects less visible and decreases the detection range of air-to-air targets.

2.10 Multiple Imaging (ghost images)

Explanation: Multiple imaging is observed only at night or in very dark ambient light

Figure 2.15: An example of halation.

conditions. It is the appearance of two or more images of a single object or light source. It is caused by light rays reflecting off the inner and outer surfaces of the transparency and back into the pilot's eye. Secondary images may vary in location and intensity with respect to the primary image. (See figures 2.16 - 2.19.)

Inspection: Multiple images are observed by looking through the transparency at night (or in a dark environment) at bright light sources. They appear as fainter images of the lights around the primary image.

Measurement: The angular displacement of the secondary images from the primary image may be measured following ASTM F 1165. The intensity ratio of the images may also be measured, although a formal procedure does not yet exist.

Visual Effect: In most cases multiple images are simply distracting. In extreme cases, they may give the pilot false motion cues, such as an inaccurate perception of approach velocity or rate of descent during nighttime landing.

2.11 Reflections (cockpit reflections)

Explanation: Reflections from transparency surfaces of cockpit objects (glare shield, flight suit, helmet, etc.) or instrument lights interfere with the aircrew's out-of-the cockpit vision. The reflections are most significant at night or in bright sunlight conditions.

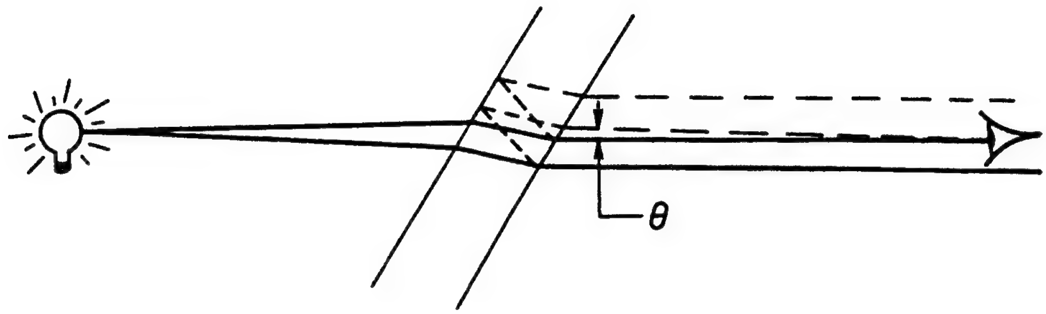

Figure 2.16: Illustration showing how multiple images are perceived.

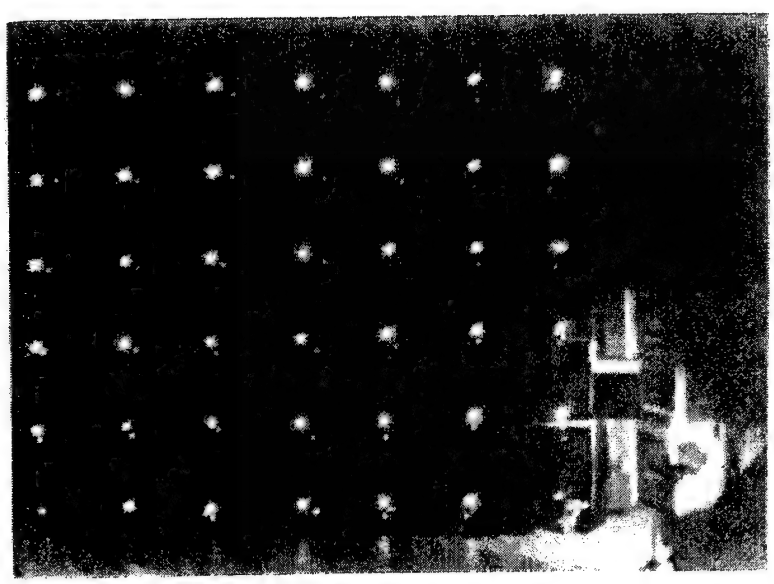

Figure 2.17: Multiple Imaging of a 7 X 7 light array.

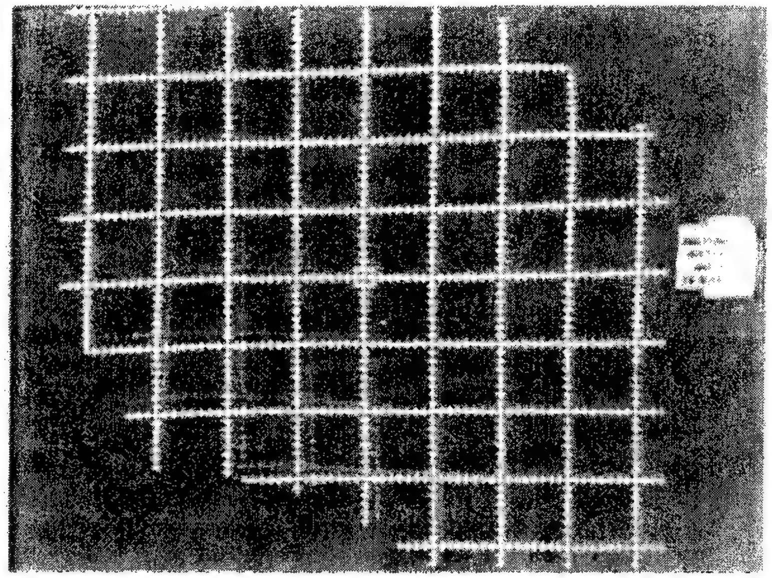

Figure 2.18: Multiple Imaging of a 6" grid board.

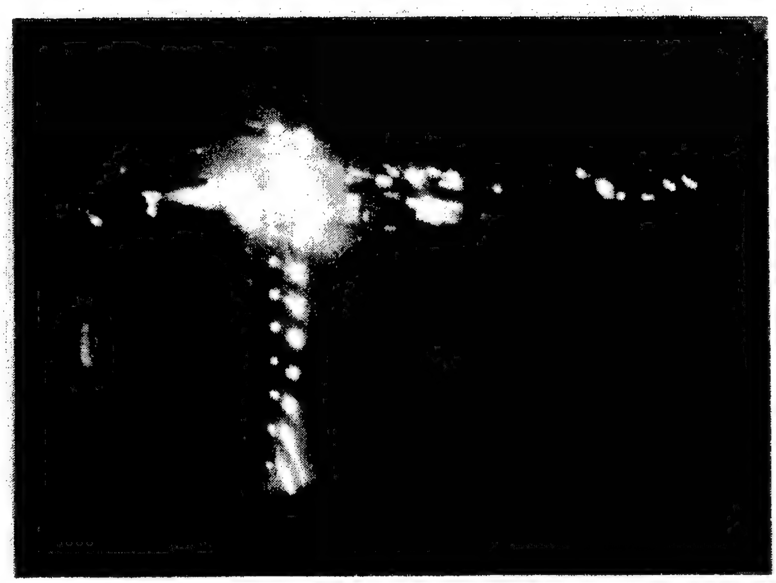

Figure 2.19: Multiple Imaging of lights through a B-1B transparency. (This transparency was later removed from the aircraft for objectionable multiple imaging.)

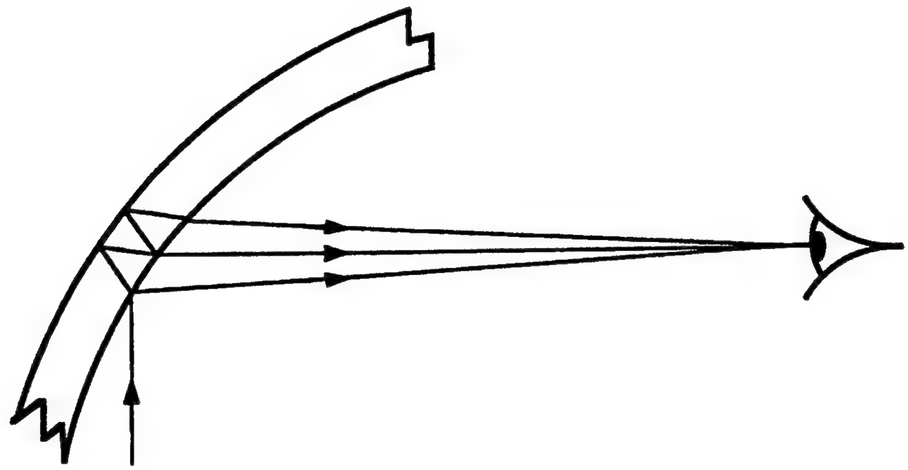

Figure 2.20: Illustration of how internal reflections occur.

Inspection: Reflections are easily observed visually under a variety of conditions.

Measurement: The reflectivity of a transparency may be measured photometrically. A new ASTM standard method is currently being published which details the measurement procedure.

Visual Effect: Reflections on the transparency reduce the contrast of out-of-the-cockpit objects and may even obscure these objects.

Figure 2.21: Reflections of the glare shield.

Comments

3.1 Notice to Aircrews and Maintenance personnel

By reading this technical report you may have learned of some optical defects of transparencies of which you previously were not aware. Now that you know about these characteristics, there may be a natural tendency to direct more of your attention to transparency optical quality, and perhaps be more critical of the transparencies which you are now flying. Undoubtably you will experience firsthand some, and perhaps many, of these characteristics;

This is not necessarily reason to have these transparencies removed from the aircraft.

Acceptable transparencies will exhibit many of these characteristics to some degree. It is only when these features become excessive that removal of the transparency is in order. This, of course, is a matter of judgement. It is probable that if you did not object to the transparency prior to reading this report, then the transparency is acceptable. Please use discretion when determining whether a transparency should be removed. If it is removed, however, carefully document the reasons for removal. Use this report as a guide so the reasons for removal are correctly and accurately identified.

3.2 General Comments

This report provides textual and pictorial information on the optical characteristics encountered in aircraft transparencies. There are measurement procedures available for quantifying most of these characteristics. However, the procedures for some of these, such as distortion, are still not satisfactory from the standpoint of being able to relate the measurement of

distortion (grid line slope) to the subjective visual effect of the distortion. New procedures and methods of relating the values produced by these procedures of measurement are in development. There is still much work to be done to accurately characterize the optical effects of aircraft windscreens and their effects on visual performance.

Any questions concerning this report or current work in the area of characterizing the optical effects of aircraft windscreens should be directed to:

AAMRL/HEF
Wright-Patterson AFB, Ohio 45433-6573

Phone: (513) 255-7585
Autovon 785-7585

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AEROSPACE TRANSPARENCY RESEARCH
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> This report presents a glossary of terms relating to aircraft windscreens, canopies, and transparencies. It addresses the need to have a single reference source, which provides a common vocabulary for use by designers, materials engineers, manufacturers, evaluators, maintenance personnel, and user agencies concerned with aircraft transparencies. Its intent is to facilitate and enhance communication between these disciplines by clarifying and defining terms used within the aircraft transparency industry.

Bartell, R. J., Unger, S. E., & Task, H. L. (1993). ***Backscatter haze device for measurement of haze in aircraft transparencies.*** (Report No. AL/CF-TR-1993-0102). Wright-Patterson AFB, OH: Armstrong Laboratory. (DTIC No. ADA275127)

> The method currently used throughout the aircraft transparency industry to measure haze is ASTM Test Method D1003. This procedure was originally developed for applications involving small, thin, and flat transparent parts. Major limitations of Test Method D1003 include its restriction to small, flat samples and its requirement for having the source and detector on opposite sides of the sample under test. In order to facilitate field-testing of installed aircraft windscreens, a test method was developed which overcomes the limitations of Test Method D1003. The new method determines haze values by measuring the amount of light backscattered off the surface of the transparency under test. A prototype instrument was developed and tested against D1003. These results of those tests are presented. The new instrument consists of an integrating sphere, a mechanically chopped incandescent light source, a silicon detector, and supporting electronics. This report describes the device, which is based on US Patent Number 4, 687, 338, in detail. Use of this type of device in the field could provide quantitative data for determining when an installed aircraft windscreen should be replaced or refinished in place.

Eggleston, R. G. (1978). **The effect of optical distortion on visual acuity.** *Proceedings of the 49th Aerospace Medical Research Association Meeting*. New Orleans, LA: Aerospace Medical Research Association.

> Given the fact that distortion is inherent in any aerodynamically efficient windshield design, it is important to determine its effects on the vision of aircrew members. Effective vision is needed for sighting and tracking both airborne and ground targets,

for safely performing aerial refueling and formation flying, and for collision avoidance during every phase of flight, including ground taxiing. Since all of these flying tasks rely on good visual acuity, any degradation in acuity resulting from windshield distortion could adversely effect aircrew safety and overall mission performance.

Due to the installation angle, curvature, thickness, and multi-layered plastic construction of the new bird impact resistant (BIRT) windshield for the F-111, it is plagued with the highest levels of distortion currently found in any operational Air Force aircraft. Distortion is particularly severe in the forward portion and around the margins of the windshield. Five levels of distortion in these areas of the F-111 windshield were chosen for investigation in the present study. These areas provided a good sampling of the total range of magnitudes of distortion found in curved aircraft windshields. The purpose of the study was to determine the effect of these levels of distortion on visual resolution acuity.

Eggleston, R. G. (1978). **A method of visual inspection of aircraft transparencies.** In R. E. Wittman (Ed.), *Conference on Aerospace Transparent Materials and Enclosures.* (Report No. AFFDL-TR-78-168, pp. 453-463). Wright-Patterson AFB, OH: Air Force Flight Dynamics Laboratory. (DTIC No. ADA065049)

Historically, the visual inspection process has typically lacked structure and definition, and has consequently varied considerably in its implementation among aircraft transparency quality control inspectors. Thus, visual quality judgments rendered in the visual inspection process are likely to be unreliable. In this study, a systematic visual inspection procedure was used to assess the severity of distortion in a controlled viewing situation. Experienced quality control inspectors evaluated the severity of distortion observed in a sample of F-111 forward transparencies. The psychophysical scaling method of magnitude estimation was used to rate the perceived severity of distortion for each windshield against an arbitrarily selected standard windshield. Appropriate numerical values are assigned to the windshields by the judges to represent the relationship of the windshields to the standard. It was found that experienced quality control inspectors could use the magnitude estimation procedure to reliably scale the F-111 windshields. In general, the magnitude estimation procedure was highly suited to the task of evaluating aircraft windshields for distortion and could easily be used to evaluate other parameters of the visual quality of aircraft transparencies such as rainbowing and multiple imaging.

Genco, L. V. (1984). ***Aircraft transparencies and aircrew visual performance.*** (Report No. AFAMRL-TR-84-005). Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Laboratory.

New aircraft designs have called for significant changes in the structural design of aircraft transparencies (windscreens and canopies). In some cases, vision throughout the transparency is degraded by optical influences of structural design or ageing

processes. In other cases, additional optical components (HUDs, visors, sunglasses, etc.) interact with the windscreen to influence visual perception.

Some of these visual problems can be alleviated by educating the pilot, the quality control inspector, the base optometrist and the flight surgeon in causes and effects of optical defects. This report is an explanation of basic visual processes used during flight, how they are affected by aircraft transparency optics, and some of the expected (and unexpected) complaints associated with the problems.

Genco, L. V. (1982). ***Angular deviation and its effect on HUD-equipped aircraft weapons sighting accuracy.*** (Report No. AFAMRL TR-82-43). Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Laboratory. (DTIC No. ADA122547)

At present, all forward windscreens (or canopies) installed on HUD-equipped aircraft are measured to determine their angular deviation, or induced aiming error. Standards have been set to accept only those transparencies, which cause little aiming error, and at least one aircraft HUD fire control computer is provided with a means to compensate for the remaining error. This report is a summary of several of the multitudinous methods used to measure angular deviation for most HUD-equipped aircraft, with an explanation of the comparative accuracy of each method when applied to weapons aiming at operational sighting ranges. The advantages and disadvantages of each quality control system are discussed, and an attempt is made to reconcile the values of each system for sighting accuracy comparisons. A recommendation is made for a standardized method of measurement, which is relatively error free, and best relates to operational use of the aircraft.

Genco, L. V. (1983). **Optical interactions of aircraft windscreens and HUDs producing diplopia.** In W. L. Martin (Ed.), *Optical and Human Performance Evaluation of HUD (Head-Up Display) Systems Design.* (Report No. AFAMRL-TR-83-095, pp 20-27). Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Laboratory. (DTIC No. ADA140601)

The Air Force is in the process of evaluating new, wide field of view head-up displays (WFOV HUDs) capable of presenting an enhanced array of visual imagery to pilots of modern aircraft. The wider fields of view through the WFOV HUD optics are achieved by using either conventional optics (as in the AFTI HUD), or holographic optical components (as in the LANTIRN HUD) to enlarge the binocular portion of the field of view (BFOV). In each of these designs, the portion of the FOV available for simultaneous use by both eyes, and the total instantaneous FOV is significantly larger than that found in "standard" HUDS. Several pilot complaints have been received concerning double vision (diplopia) experience while using LANTIRN F-16 HUD in a test aircraft. Specifically, a complaint was made of seeing two targets while maintaining a single image of the display-generated aiming symbol. Statements have also been made concerning the doubled appearance of the pipper, while maintaining a single image of the target. These complaints are based on visual errors induced in the pilot's binocular (two-eyed) visual system by the HUD and the

canopy optics. This paper will explain why these visual problems were experienced, and recommend some solutions for any WFOV HUD system, whether it includes holographic optics, as in the LANTIRN system, or "conventional" optics, as in the AFTI system.

Genco, L. V. (1983). **Visual effects of F-16 canopy/HUD integration.** In S.A. Marolo (Ed.), *Conference on Aerospace Transparent Materials and Enclosures.* (Report No. AFWAL-TR-83-4154, pp. 793-807). Wright-Patterson AFB, OH: Air Force Wright Aeronautical Laboratories. (DTIC No. ADA140701)

Future fighter aircraft will be fitted with Wide Field of View Head Up Displays (WFOV HUDs), and probably, curved windscreens. Initial flight tests with a WFOV LANTIRN HUD in an F-16 fighter results in test pilots complaining of several visually related problems. One of the complaints was of double vision – either two aiming symbols or two targets were seen when the pilot kept both eyes open. Other complaints included those of blurred images and a change in depth perception when looking through the HUD-canopy combination.

This paper is a report of some of the work done by the Air Force Aerospace Medical Research Laboratory in an attempt to determine both the source of the problem and possible solutions. After a series of laboratory and field tests, some problems were found to be due to excessive retinal disparity or parallax error between the two eyes, induced by a difference in collimation or angular deviation between light from the target and light from the HUD. The angular difference between the parallel light rays from the CRT and the divergent light rays passing through the canopy and combining glass was sufficient to "split" the images in the visual system.

Recommendations are given for the maximum parallax error tolerated by the human visual system in a WFOV HUD – canopy combination. A companion paper by H. Lee Task, Ph.D., describes more of the optical background and measurements.

Genco, L. V., & Task, H. L. (1981). ***Aircraft transparency optical quality: new methods of measurement.*** (Report No. AFAMRL-TR-81-21). Wright-Patterson AFB, OH: Aerospace Medical Research Laboratory. (DTIC No. ADA096183)

This report describes some traditional methods of measuring distortion in aircraft transparencies. A more expedient means of interpreting photographic distortion data via computerized digital analysis of the photo is also described. Finally, two new devices are introduced: one that measures angular deviation with extreme accuracy in a relatively small space and one that brings laboratory accuracy to field optical measurements. These latter devices employ state-of-the-art components and knowledge to provide extreme accuracy and usefulness.

Gomer, F. E., & Eggleston, R. G. (1978). **Perceived magnitudes of distortion, secondary imaging, and rainbowing in aircraft windscreens.** *Human Factors*, 20(4), 391-400.

Distortion, secondary imaging, and rainbowing are perhaps the most critical optical problems inherent in windshields designed for high performance aircraft. Although manufacturers are required to inspect each windshield and render perceptual decisions about the severity of these optical problems, the procedures followed by different observers vary greatly. As a result, visual quality control can be improved significantly. This report describes the successful application of a psychophysical method for scaling visual judgments concerning the apparent magnitudes of distortion, secondary imaging, and rainbowing in current Air Force F-111 windshields.

Grether, W. F. (1973). ***Optical factors in aircraft windshield design as related to pilot visual performance.*** (Report No. AMRL-TR-73-57). Wright-Patterson AFB, OH: Aerospace Medical Research Laboratory. (DTIC No. AD767203)

The slope and curvature of aircraft windshields that are optimum for high-speed flight cause optical degradation of pilot vision in the forward direction. This report presents a survey of the literature bearing on the conflict between aerodynamic and visual requirements. The optical effects of windshield slope (or angle of incidence) and curvature area reviewed, in terms of displacement, deviation, distortion, binocular deviation, reflections, multiple images, haze, transmission loss, and reduced resolution. Included in the review are discussions of windshield design practices in recent military aircraft as well as optical standards and tolerance contained in current military specifications. The review also provides a discussion and research data on pilot visual performance as affected by windshield design factors, and a small sample of pilot opinions concerning the visual problems caused by the windshield of the F-111 aircraft. The report concludes with some suggestions for further studies that would assist in making choices concerning windshield design.

Harris, J. S., & Harding, K. G. (1981). ***Study and evaluation of existing techniques for measuring aircraft windscreen optical quality: development of new techniques for measuring aircraft windscreen optical distortion.*** (Report No. AFAMRL TR-81-25). Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Laboratory. (DTIC No. ADA097731)

A program to study and develop techniques for evaluating windscreen optical quality was conducted in support of the Aerospace Medical Research Laboratory's windscreen program. The bird impact resistant transparency (BIRT) windscreens under study were both thick and lightweight laminated components developed to reduce the threat to low-flying aircraft from bird impact. Visual performance is affected by several optical variables of the windscreen; however, this program addressed only the techniques used to evaluate optical distortion. Results of the study indicated that grid board photographic techniques are simple and easy to perform, but errors as large as 20% occur in manual data reduction. Point-by-point measurement of F-111 windscreen optical distortion has shown that this technique provides high accuracy, but is very time consuming. Point-by-point measurements of four

representative F-111 windscreens have shown that angular deviations will not usually exceed 40 minutes of arc and that localized optical distortion effects are characterized by large, highly localized variations in angular deviations. Techniques using raster scanned laser probe beams in conjunction with ratio reflecting screens and holographic lenses could provide the capability for high-speed evaluation of optical distortion in windscreens. The technique to be developed for quantified evaluation of optical distortion should be a grid board photographic system. A grid board digitization system is described to eliminate data reduction errors.

Kama, W. N. (1989). **Measures of distortion: are they relevant?** In S. A. Marolo (Ed.), *Conference on Aerospace Transparent Materials and Enclosures.* (Report No. WRDC-TR-89-4044, Vol. 2, pp.1072-1093). Wright-Patterson AFB, OH: Wright Research and Development Center. (DTIC No. ADA210201)

Based on the results obtained from a pilot study, an experiment was conducted to determine how well current measures of optical distortion in aircraft transparencies (grid line slope, lens factor and displacement grade) related to the subjective assessment of this phenomenon by human operators. A total of 20 subjects were asked to perform several tasks, each of which would yield a measure (subjective and objective) of the "amount" of distortion present in 13 test windshields. The subjective tasks included a magnitude estimation task (using the actual windshields and photos of the windshields) – in which all windshields were compared to and a "referee" windshield; and a ranking test, in which subjects ranked distortion photos of each windshield from the least objectionable to the most objectionable. The objective task consisted of measuring distortion using the measurement techniques of grid line slope, lens factor and displacement grade. The results obtained indicated no relationship between a human operator's qualitative assessment of a windshield and the quantitative measures obtained.

Kama, W. N. (1994). **Round-robin testing to determine the precision and accuracy in measuring multiple images in aircraft transparencies.** In S. A. Marolo (Ed.), *Conference on Aerospace Transparent Materials and Enclosures Volume II.* (Report No. WL-TR-94-4084, Vol. 2).Wright-Patterson AFB, OH: Materials Directorate Wright Laboratory Material Command. (DTIC No. ADA283926)

A round-robin testing study was conducted to determine the precision and accuracy of a test method used to measure multiple images in aircraft transparencies. A total of 12 measurement technicians from six laboratory facilities served as subjects. Stimulus materials for this study were four 8 x 10, black and white, multiple imaging photographs which represented four different camera-to-array distances – 15, 23, 23.5 and 25 feet. Each photo was created by photographing a light array of known size at a specified distance from the design eye position of the windshield. The subject's task included (1) determining a scale factor (used to relate linear distances on the photograph to actual angular distances as seen from the design eye position) for each of the four photos to be measured and (2) making linear measurements in millimeters (mm) for each light on the photograph to determine the separation between the

secondary and primary images. The linear measurements were made using a pair of digital calipers. All subjects were carefully instructed on how to calculate the scale factor, how to use the digital calipers, and the manner in which they were to make the linear measurements, from the "center" of the secondary image to the "center" of the primary image. Subjects measured each photo twice so that a determination of the repeatability of their measurements could be made. Subject performance was evaluated with respect to the performance of two measurement technicians who were highly skilled and proficient in using this measurement technique. Their scores were used as the baseline for this study. Findings from this study indicated that (1) measurements were highly accurate, differing on average from the baseline score by 0.37 mm, (2) repeatability (precision) was also high, scores differing, on average, between trials one and two by 0.08 mm, and (3) the calculated scale factors were larger, on average, by 0.24 mrad/mm, than the baseline scores.

Kama, W. N. (1983). **Visual perception through windscreens: effects of minor occlusions and haze on operator performance.** In S. A. Marolo (Ed.), *Conference on Aerospace Transparent Materials and Enclosures.* (Report No. AFWAL-TR-83-4154, pp. 825-848). Wright-Patterson AFB, OH: Air Force Wright Aeronautical Laboratories. (DTIC No. ADA140701)

Current specifications and acceptance procedures regarding the size and number of minor defects (optical occlusions) permitted on aircraft transparencies reflect a marked lack of uniformity – size requirements ranging from 0.035 to 0.25 inch and numbers allowed varying from 1 per square foot to 20 per zone. Additionally, there is, at the present time, no objective means for determining when a transparency should be replaced due to the amount of halation found in it. To address these two problems, two experiments were devised and performed in the Windscreen Facility of the Air Force Aerospace Medical Research Laboratory. The first study sought to determine the effects of size and number (density per unit area) of minor optical defects contained in an aircraft transparency on the performance of a simulated air-to-air target acquisition task while the second sought to determine what relationship, if any, existed between the amount of haze emanating from a transparency and the amount of an observer's field-of-view (FOV) or visual field that is "lost" (rendered unusable) due to the presence of the haze. Data generated from the first study can be used to relate visual performance to requirements currently specified in the various specifications and standards as well as contribute to the formation of new visual/optical specifications and standards. Data from the second study can be used in the development of an objective technique for determining when aircraft transparencies should be replaced because of haze. This paper describes the procedures used and the results obtained in these two studies.

Kama, W. N., Barbato, M. H., & Hausmann, M. D. (1983). ***The effect of haze on an operator's visual field and his target detection performance.*** (Report No. AFAMRL-TR-83-066). Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Laboratory. (DTIC No. ADA138330)

A study was conducted to determine what type of relationship, if any, exists between the amount of haze emanating from a transparency and the percent of an operator's visual field that is "lost". The effect of this haze on his ability to perform a target detection task was also determined. Ten subjects performed a simple target detection task in which they were required to indicate when they could see a slowly moving, 1.0 minute of arc, 80% contrast target that traveled in 8 (0, 45, 90, 135, 180, 225, 270, or 314 degrees) different angular directions from the center of a background screen towards the periphery. The subjects performed this task while looking through haze test panels mounted at 90 degrees, 63 degrees or 45 degrees to their line of sight and which when illuminated by a bright light source mounted at the center of the background screen resulted in haze conditions of 2%-3.5%, 5%-10%, 15%-26% or 25%-48%. A baseline condition in which no test panel was interposed between the subject, the task and the bright light source was also administered. Subject performance was evaluated in terms of (1) the distance the target had moved before being seen, and (2) the number of times that it was not detected. The results of this study indicated that as the percent of haze present in a transparency increased, the percent of an operator's background FOV that is occluded also increased but that the percent of targets detected decreased. It is suggested that these two relationships can be used as an objective yardstick for arriving at decisions as to when a transparency should be replaced due to the amount of haze present in it.

Kama, W. N., & Genco, L. V. (1982). ***The effect of size and number (density) of minor optical occlusions on target detection performance.*** (Report No. AFAMRL-TR-82-48). Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Laboratory. (DTIC No. ADA122546)

A study was conducted to determine the effect of size and number (density per unit area) of minor optical defects contained in an aircraft transparency on aircrew visual performance. Eight subjects performed a target detection task while looking through 13 simulated "windscreen" test panels. These panels contained defects of size 0.032, 0.043, or 0.35 inches in diameter that varied in number from 11, 22, 33, or 44 per panel. The targets to be detected simulated an aircraft with a frontal plan of 40 feet located at a range of 24,500 feet (0.5 minutes of arc) or 49,000 feet (1.0 minute of arc) being viewed under fairly clear atmospheric conditions (80% contrast) or poor atmospheric conditions (10% contrast). Subject performance was measured in terms of time to detection and percent correct detection. The results obtained indicated that target size and target contrast significantly affected performance, however, the number and size of defects on the "windscreen" had no effect on performance. Based on this latter finding, it is concluded that current standards and specifications concerning the number and size of minor optical defects permitted on aircraft transparencies may be safely relaxed without adversely affecting aircrew visual performance. A recommendation is also made that an alternative method for determining the "goodness" or "badness" of a transparency be employed. Such a method would be used on a percentage of a given area of the transparency that may be obstructed by optical defects.

Kraft, C. L., Anderson, C. D., Elworth, C. O., & Larry, C. (1977). ***Windshield quality and pilot performance.*** (Report No. AMRL-TR-77-39). Wright-Patterson AFB, OH: Aerospace Medical Research Laboratory. (DTIC No. ADA048457)

Two experimental investigations were performed with C-141 pilots making aircraft landings with a 727-200 flight-crew training simulator mounted on a three-degree-of-freedom motion base. The terrain image was computer-generated and the 1000 TV line, full color scene was displayed at optical infinity with a resolution of 2.9 arc minutes. All pilots were extensively tested for visual skills. Optical distortion panels between the pilot and the visual scene simulated a range of windscreen image qualities from excellent to poor. One study used 8 pilots, 4 windscreen qualities, 2 times-of-day and 2 visibility conditions. A second study used 6 pilots, 3 windscreen qualities, 2 times-of-day, and 4 replications. In both studies, ten dependent measures were taken of pilots' performance.

Decreased windscreen optical quality increased centerline deviations at touchdown point. Windscreen quality and time-of-day significantly interacted. Night approaches with poor windscreens were significantly above glide slope, but on glide slope with better windscreens. Approaches were low for all windscreens in daytime landings. Poor optical quality windscreens caused apparently more cautious night landings: higher faster approaches, more rapid descents and touchdowns that were harder and further down the runway. Recommendations are made for measuring windscreen optical quality effects on flight performance.

LaPuma, P. T., & Bridenbaugh, J. C. (1988). ***Specifications and measurement procedures for aircraft transparencies.*** (Report No. AAMRL-TR-88-058). Wright-Patterson AFB, OH: Armstrong Aerospace Medical Research Laboratory. (DTIC No. ADA209396)

This report is a summary of the specification requirements for optical quality for several military aircraft transparencies. It is intended to provide the design engineer with an easy reference to a majority of the accumulated historical information concerning optical quality.

MacLeod, S., & Eggleston, R. G. (1980). ***Pilot reactions to optical defects found in F-111 bird impact resistant windscreens.*** (Report No. AFAMRL TR-80-4). Wright-Patterson AFB, OH: Aerospace Medical Research Laboratory. (DTIC No. ADA093937)

A field study was conducted to assess the scope and severity of mission related optical problems associated with the new F-111 Bird Impact Resistant Transparency (BIRT) windscreen. Data for this study was gathered from an 81-item questionnaire and used to scale the opinions of 33 USAFE pilots. Principle findings indicate that: (1) distortion is perceived as the most disruptive optical factor followed in order by multiple images, haze and rainbowing; (2) the worst combination of optical defect and flight task is multiple images during night approach and landing; (3) the extent to which BIRT optical problems are perceived as impairing mission performance is

sufficiently great to further justify research for improving windscreen optical quality; (4) pilots with very limited amounts of BIRT flying time (20-80 hours) are less likely to perceive windscreen optical problems than a middle experience group (with 100 to 180 flying hours). This difference is attributed to a lack of exposure to the optical effects; and (5) pilots with relatively extensive BIRT flying experience (over 200 hours) are also less prone to perceive windscreen problems than the middle experience group. This difference is attributed to the effect of a period of adjustment to the optical anomalies.

Marasco, P. L. (2000). ***An examination of optical scatter from aerospace transparencies and its effect on vision.*** Unpublished doctoral dissertation, University of Dayton, Ohio.

Scattered light from transparent materials is an issue impacting many industries, including the aerospace industry. Haze, the ratio of scattered light to the total light transmitted through a transparent material, is often used to specify the quality of a transparency and as a metric to estimate the impact of light scattered from the transparency on visual performance. However, research has shown that haze does not correlate well with visual performance losses (Kang, 1996). This effort examines the measurement of haze, its limitations, and the behavior of haze when used to measure aerospace transparencies. The effort further compares this standard haze measurement with an angle-resolved technique for measuring scattered light, showing why haze should be a poor predictor of visual performance. This research applies diffractive techniques in an attempt to predict and model the angular behavior of scattered light. Visual performance for viewing targets through a veiling luminance is predicted for a particular set of target conditions. This research treats visual performance to determine the accuracy of the visual performance model.

Merkel, H. S. (1989). **Recent advancements in optical measurements in transparencies.** In S. A. Marolo (Ed.), *Conference on Aerospace Transparent Materials and Enclosures.* (Report No. WRDC-TR-89-4044, Vol. 2, pp. 1072-1093). Wright-Patterson AFB, OH: Wright Research and Development Center. (DTIC No. ADA210201)

In recent years, new procedures have been developed for measuring transparency optical parameters. This paper discusses four procedures that have provided new means by which manufacturers and users of transparencies may quantify critical optical parameters. For each procedure three factors will be addressed: 1) the background of the procedure; 2) the requirement for the procedure and considerations made in its development; and 3) a summary of the procedure. The final section of the paper will discuss some areas of current investigation that are likely to lead to enhancements of existing measurement procedures.

Merkel, H. S., & Task, H. L. (1989). ***An illustrated guide of optical characteristics of aircraft transparencies.*** (Report No. AAMRL-TR-89-015). Wright-Patterson AFB, OH: Armstrong Aerospace Medical Research Laboratory. (DTIC No. ADA214565)

Aircraft transparencies are susceptible to numerous optical characteristics, which may impact the visual performance of the aircrew. These characteristics range in severity from simply distracting to hazardous. This report describes and illustrates the ten most common of these optical characteristics. It may be used as a guide by aircrews, maintenance personnel, and others working with transparencies to assist them in accurately identifying transparency optical defects.

Muick, C. J. (1978). ***Lexicon of aircraft transparency terms.*** (Report No. AMRL-TR-78-122). Wright-Patterson AFB, OH: Aerospace Medical Research Laboratory. (DTIC No. ADA071319)

This lexicon deals with terms and definitions peculiar to personnel working with aircraft transparent enclosures. All types of material currently used in the fabrication of transparent enclosures (acrylic, glass, polycarbonate) are addressed. Terms are either specific or general when applied to materials; and vision/optics terms, in most instances, are common to windscreens, canopies and windows.

Pinkus, A. R., & Hausmann, M. A. (2003). ***Interlaboratory study (ILS) for ASTM F 428-83, the standard test method for intensity of scratches on aerospace glass enclosures.*** (Report No. AFRL-HE-WP-TR-2003-0012). Wright-Patterson AFB, OH: Air Force Research Laboratory.

The American Society for Testing and Materials (ASTM) develops and publishes standardized test methods. Each test method requires a precision and bias statement so organizations that apply the method know its inherent reproducibility (between-laboratory variability) and repeatability (within-laboratory variability). Reproducibility and repeatability for this test method were determined by conducting an interlaboratory study (ILS) as outlined in ASTM E 691. This report, which conforms to the ILS reporting format required by ASTM, describes the study that was conducted for ASTM test standard F 428-83, Intensity of Scratches on Aerospace Glass Enclosures.

Scratches exist on all glass surfaces. Usually, cleaning procedures cause very fine scratches that are not visible when looking through the glass. Visible scratches may be distracting to an observer looking through a transparent aerospace enclosure. Therefore, a procedure to define scratches is useful. A visual comparison is made between a set of graded scratch standards (adjuncts) and a scratch on the glass transparency to determine its relative intensity. A visual standard is used because it is not practical to measure the dimensions of the fine scratches.

Pinkus, A. R., & Hausmann, M. A. (2003). ***Interlaboratory study (ILS) for ASTM F 548-01, the standard test method for intensity of scratches on aerospace transparent plastics.*** (Report No. AFRL-HE-WP-TR-2003-0009). Wright-Patterson AFB, OH: Air Force Research Laboratory.

The American Society for Testing and Materials (ASTM) develops and publishes standardized test methods. Each test method requires a precision and bias statement so organizations that apply the method know its inherent reproducibility (between-laboratory variability) and repeatability (within-laboratory variability). Reproducibility and repeatability for this test method were determined by conducting an interlaboratory study (ILS) as outlined in ASTM E 691. This report, which conforms to the ILS reporting format required by ASTM, describes the study that was conducted for ASTM test standard F 548-01, Intensity of Scratches on Aerospace Transparent Plastics.

Scratches exist on virtually all transparent plastic surfaces. Usually, cleaning procedures cause very fine scratches that are not visible when looking through the plastic. Visible scratches may be distracting to an observer looking through an aerospace transparent plastic. Therefore, a procedure to define scratches is useful. A visual comparison is made between a set of graded scratch standards (adjuncts) and a scratch on the plastic transparency to determine its relative intensity. A visual standard is used because it is not practical to measure the dimensions of the fine scratches.

Pinkus, A. R., & Task, H. L. (1997). **The effects of aircraft transparencies on night vision goggle-mediated visual acuity.** Proceedings of the 35th Symposium SAFE Association, (pp. 93-104).

Night vision goggles (NVGs) are currently used in a wide variety of military aircraft that were not originally designed for NVGs. Likewise, the windscreens and canopies on these aircraft were not designed with NVGs in mind. Present day windscreens and canopies typically have one or more specialized coatings applied to them. These may be reasonably transparent for visible wavelengths but not so transparent for near infrared light to which the NVGs are sensitive. It was hypothesized that the major mechanism by which aircraft transparencies affect the operation of NVGs is through reduced light levels. This would mean that the key characteristic of interest for determining the effect of an aircraft transparency on the operation of the NVGs would be its transmission coefficient calculated using the spectral sensitivity of the NVGs. This hypothesis was tested by investigating visual acuity performance of trained observers viewing through NVGs for three levels of ambient illumination (1, 2 and 5 times starlight) and three levels of NVG-weighted transmissivities (58, 76 and 100%). In addition, two levels of contrast were included in the study (20 and 70% modulation contrast). Three trained observers determined the orientation of a Landolt C using a two-alternative forced-choice step paradigm. A luminance-based model was developed to smoothly combine the effects of illumination level and transmission level for each contrast thus supporting the hypothesis. In addition, the results demonstrate the significant difference between individual observer's performance level and the increased difficulty (higher variability) of performance at lower contrast levels.

Pinkus, A. R., & Task, H. L. (1998). ***Interlaboratory study (ILS) for the determination of the angular displacement of multiple images in transparent parts.*** (Report No. AFRL-HE-WP-TR-1998-0011). Wright-Patterson, AFB, OH: Air Force Research Laboratory. (DTIC No. ADA345368)

An Interlaboratory Study (ILS) was undertaken in order to determine the precision of the test method for measuring the angular displacement of multiple images by transparent parts. Multiple imaging is defined as the angular separation of secondary images from their respective primary images as viewed from the design eye position of an aircraft transparency. Newer aircraft now utilize thick, curved, highly angled transparencies resulting in multiple imaging being more frequently cited as an optical problem by pilots. Secondary images vary in intensity and displacement across the transparency thus giving the observer deceptive cues of attitude, velocity and approach angle. ASTM test method ASTM F 1165-88 standardizes the measurement technique. This ILS determined the precision of this method.

Pinkus, A. R., & Task, H. L. (1998). ***Interlaboratory study (ILS) of the standard test method for measuring the night vision goggle-weighted transmissivity of transparent parts.*** (Report No. AFRL-HE-WP-TR-1998-0016). Wright-Patterson, AFB, OH: Air Force Research Laboratory. (DTIC No. ADA342777)

Night vision goggles (NVGs) are now being used in aircraft and other applications (e.g., marine navigation, surveillance, vehicles) with increasing frequency. These devices amplify near-infrared (NIR) spectral energy. A transparency may have excellent visible transmissive characteristics but could have poor NIR transmissivity. Overall visual performance (acuity) can be degraded if the observer uses the NVGs while looking through a transparency that has attenuated transmissivity in the NIR region. ASTM P 94-02, Standard Test Method for Measuring NVG-Weighted Transmissivity of Transparent Materials addresses this issue. This Interlaboratory Study (ILS) determined the precision of P 94-02. The method describes both analytical and direct measurement techniques that determine the NVG-weighted transmissivity (T_{NVG}) of transparent pieces. T_{NVG} is the integrated value (450 through 950 nm) of the spectral transmissivity of a transparent part weighted (multiplied) by both the spectral sensitivity of a given set of NVGs and the light source, divided by the integrated value of the NVGs times the light source. The higher the T_{NVG} the more compatible a transparency is with NVGs, i.e., there is more light energy available to be amplified by the goggles which usually corresponds to better visual acuity performance of the observer (finer detail seen).

Pinkus, A. R., & Task, H. L. (2001). ***Interlaboratory study (ILS) on the standard test method for measuring grid line slope (GLS) in aerospace transparencies.*** (Report No. AFRL-HE-WP-TR-2001-0104). Wright-Patterson AFB, OH: United States Air Force Research Laboratory. (DTIC No. ADA392444)

When an observer looks through an aerospace transparency, relative optical distortion may result, specifically in thick, highly angled, multi-layered plastic parts. Distortion

occurs in all transparencies but is especially critical to aerospace applications such as combat and commercial aircraft windscreens, canopies and cabin windows. This is especially true during certain operations such as takeoff, landing and aerial refueling. It is critical to be able to quantify optical distortion for procurement activities. The test method covers apparatus and procedures that are suitable for measuring the grid line slope (GLS) of transparent parts including those that are small or large, thin or thick, flat or curved, or already installed. This ILS determined the test method's measurement precision.

Pinkus, A. R., Task, H. L., & Dixon, S. A. (2003). ***Transmissivity and Night Vision Goggle Compatibility of Data of Select Aircraft Transparencies.*** (Report No. AFRL-HE-WP-TR-2003-0015). Wright-Patterson AFB, OH: Air Force Research Laboratory.

This document is a compilation of spectral transmissivity data measured from numerous aircraft transparencies. The spectral transmissivity of each part was measured from wavelengths of 450 nm through 950 nm. Some parts were also measured at several different angles relative to the optical axis of the spectroradiometric instrument. The measurements yielded both visible light and near infrared (NIR) spectra. The NIR data were used to calculate night vision goggle-weighted transmissivity (T_{NVG}) values (Pinkus and Task, 1997). T_{NVG} is a measure of a transparency's compatibility when it is used in conjunction with night vision goggles (NVGs). NVGs utilize the NIR portion (600 nm through 950 nm) of the night sky ambient illumination. Generally speaking, the higher the T_{NVG} coefficient, the higher the NVG visual performance (Pinkus & Task, 1998a; Pinkus & Task, 1997).

Pinkus, A. R., Task, H. L. & Marasco, P. L. (2001). **Aircraft canopy porthole.** *AFRL Technology Horizons*, 2(1).

This invention describes a device and procedure that allows effective use of high-powered infrared (IR) lasers, as they are directed through the side area of an aircraft canopy, for use as designators. However, the plastic canopy naturally acts as a light conduit. The stronger the laser, the greater the amount of canopy glow, due to light being scattered, which directly interferes with the pilot's out-of-the-cockpit NVG visibility. This device is a canopy porthole that optically isolates the section through which the laser shines from the rest of the canopy. The light scatter to the rest of the canopy is greatly attenuated allowing both an increase in laser power to be realized and enhanced NVG visibility. Benefits include increased laser eye safety within the cockpit, lowered IR signature emanating from the cockpit, greater stand-off slant range, no canopy glow increase as abrasion induced light scattering occurs in aging parts.

Seid, R. C. (1981). ***Computer analysis and correction of the optical distortion in the F-111 bird impact resistant windscreen.*** (Report No. AFAMRL TR- 81-67). Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Laboratory.

The F-111 Bird Impact Resistant Transparency (BIRT) windscreen was analyzed in terms of its optical effects on the crewmember's perception of the world seen through the windscreen. A computer ray-trace program was within that traced via an iterative approach light rays from an object point in front of the windscreen, and to the pilot's design eye position behind the windscreen. From this raw data, geometric distortion, dioptric lensing, prism deviation, and the binocular effects of induced phoria and aniseikonia were calculated and presented in a series of computer plots.

Using the data, the F-111 BIRT windscreen was modified to reduce the level of distortion inherent in the BIRT design. Theoretical analyses into the sources of distortion in the F-111 windscreen design were also conducted.

Seid, R. C., & Self, H. C. (1978). ***Influence of grid board line width and spacing on windscreen distortion measurements.*** (Report No. AMRL TR-78-93). Wright-Patterson AFB, OH: Aerospace Medical Research Laboratory. (DTIC No. ADA065821)

Optical distortions of aircraft windscreens are commonly measured on photographs taken through the windscreens of a large flat Cartesian grid called a grid board. Presently there are no accepted standards for the width of the lines or the size of the squares on grid boards. This study measured the effects of these variables upon measurements of vertical and horizontal magnifications to aid in establishing standards.

Self, H. C. (1982). ***Visual judgments of optical distortion in aircraft windscreens.*** (Report No. AFAMRL-TR-81-24). Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Laboratory. (DTIC No. ADA124307)

Observer ratings of optical distortion in eleven F-111 aircraft windscreens were examined using six factory production line visual quality inspectors, six Air Force pilots, all with years of flying experience, and two observers familiar with aircraft windscreen problems. Observers looked through the windscreens at large grid boards having thin white lines on a black background. Each windscreen was rated for effect of distortion on flying performance (yes/no), acceptability (yes/no), and for position on a 0 to 5 distortion scale for eight optical distortion variables: line splitting, line bending, line banding, shimmer, magnification, other distortions, and overall distortion. High correlations were found between types of distortion. Ratings on either banding or line bending, could be used to efficiently predict overall optical distortion. Pilots and visual quality inspectors were quite close in judgments of overall optical distortion and on specific types of distortion. Pilots rated distortions very slightly worse (higher), but were appreciably more likely to rate a windscreen as influencing pilot performance. Neither lens factor nor displacement grade, alone, were significantly related to acceptability or performance affects judgments.

Self, H. C., & Task, H. L. (1980). ***Potential of optical fourier analysis for measuring windscreen distortion.*** (Report No. AFAMRL-TR-80-104). Wright-Patterson AFB, OH: Aerospace Medical Research Laboratory. (DTIC No. ADA094127)

The potential of an optical Fourier technique for measuring the optical distortion of aircraft windscreens was examined. It was hypothesized that the compactness of the harmonics of the optical Fourier transforms of vertical and horizontal square-wave targets photographed through windscreens would correlate highly with distortion in photographs of a grid board. Eleven transparent optical distortion panels were used to produce grid board pictures and vertical and horizontal transform pictures. Grid board pictures were subjectively ranked by 23 observers for amount of optical distortion. Transform pictures were ranked for compactness of the third harmonic. All three picture sets were also measured by subjective magnitude estimation. Rank correlation between grid board photograph distortion ranks and compactness ranks for the vertical Fourier transform was .950. Overall rankings of grid board distortion photographs and compactness rankings were .977. Such high statistically significant correlations show that distortion judgments from grid board photographs is accurately predictable from judged compactness of the third harmonic. Thus, the Fourier method may be useful for measuring optical distortion. Development of objective methods to measure the compactness and to calibrate such measures against conventional measurements is warranted. This development would lead to a rapid, accurate and objective method for measuring the optical distortion of aircraft windscreens.

Targove, B. D., & Provines, W. F. (1978). **F-111 windscreen phorias.** In R. E. Wittman (Ed.), *Conference on Aerospace Transparent Materials and Enclosures* (Report No. AFFDL-TR-78-168, pp. 465-476). Wright-Patterson AFB, OH: Air Force Flight Dynamics Laboratory. (DTIC No. ADA065049)

It has been hypothesized by vision scientists that varying magnitudes of windscreen distortion induce varying magnitudes of hyperphoria. Displacement grading is a current method of quantifying F-111 windscreen distortion.

In order to test this hypothesis, three F-111 windscreens of varying displacement grading were evaluated for windscreen-induced hyperphoria. "L" had a low displacement grading. "M" had a higher displacement grading but was just within the displacement grading specification. "H" had a displacement grading significantly higher than the specification. Two Helium-Neon lasers, separated by 6.4 cms., were yoked in order to simulate a pilot's binocular line of sight. The windscreens were articulated so as to facilitate an induced phoria measurement at 22 representative locations throughout each of the three windscreens. A throw distance of 10 meters from windscreen to measuring surface was utilized. At 10 meters, a vertical separation of 1 cm between the two laser spots was calculated as 0.1 of a prism diopter (almost exactly 1.0 milliradian).

The maximum induced windscreen phoria level for L was 0.2 prism diopters, M was 0.25 prism diopters and H was 0.55 prism diopters. The mean phoria levels from the 22 locations were L = 0.455, M = .1227 and H = .1364. Standard deviations were L = .0554, M = 0.813 and H = .1115. An analysis of variance, followed by a post hoc

comparison, indicated that the mean of L was significantly lower (95% confidence level) than M or H. No other significant differences between means were found. In comparing the induced vertical phoria variability of the 22 locations measured for each windscreen, it was found that H had twice the variability of induced vertical phoria compared to L and a one-third greater variability compared to M.

The data appear to indicate that if a binocular specification for vertically induced hyperphoria is appropriate, mean induced vertical hyperphoria findings are probably not meaningful as a pass/fail criterion. However, the British method of considering only the maximum vertical hyperphoria value as a criterion would appear to have some merit. In addition, it may be that windscreen vertical phoria variability may be at least as important as the maximum vertical phoria value. The use of twin lasers is not recommended for this evaluation. Time, space and equipment demands might be prohibitive. The use of binocular photographs appears to be a satisfactory method of both evaluating the maximum vertical induced phoria and induced vertical phoria variability.

Targove, B. D., & Seid, R. C. (1979). ***Paraxial opticovisual analysis of the F-111E windscreen with generic application.*** (Report No. AMRL-TR-79-107). Wright-Patterson AFB, OH: Aerospace Medical Research Laboratory. (DTIC No. ADA080143)

A portion of the F-111E Bird Impact Resistant Windscreen is analyzed utilizing paraxial optical techniques. An opticovisual analysis of likely visual effects are postulated from the paraxial optical analysis. These analyses indicate that variable meridional magnification and prism deviation variability are the significant parameters in producing deleterious binocular effects.

Task, H.L. (1996). **Development and evaluation of a device to measure the severity of aircraft transparency crazing.** *SAFE*, 26(1), 8-18.

Aircraft transparencies such as cabin windows, canopies and windscreens are typically made from plastic and can become crazed due to mechanical, chemical, or environmental stress. Crazing is the name given to the condition of the transparency wherein its surface is riddled with tiny micro-cracks. These micro-cracks act as mirrors causing potentially debilitating sunlight to be reflected into the visual path of one looking through the transparency. Although this phenomenon has been apparent for a long time, there has never been a procedure or device developed to determine the severity of the crazing. Measurements were made on crazed commercial aircraft cabin windows to determine some of the basic characteristics of the micro-cracks. A device was designed and fabricated to obtain quantitative assessment of the severity of the craze level of several transparencies. Using a modified version of the original device, the crazing characteristics of several transparencies were assessed including orientation and moisture effects. Comparisons were made with an alternative prototype device recently developed by Quantas Airways for their internal use in maintenance procedures with respect to crazed cabin windows.

Task, H. L. (1983). **Optical effects of F-16 canopy-HUD integration.** In S. A. Marolo (Ed.), *Conference on Aerospace Transparent Materials and Enclosures.* (Report No. AFWAL-TR-83-4154, pp. 808-824). Wright-Patterson AFB, OH: Air Force Wright Aeronautical Laboratories. (DTIC No. ADA140701)

The F-16 heads-up display (HUD) provides the pilot with visual information in symbology form that is overlayed on the outside world scene in the forward viewing direction. This superposition of HUD symbology and outside world scene is done by using an optical combiner (beam splitter) that is part of the HUD optical system. One of the critical items of information that is displayed on the HUD is the aiming reticle that is used for air-to-air and air-to-ground weapon aiming. In order to be effective, it is essential that the aiming reticle be accurately bore-sighted to the weapon system. This requires a careful integration of the optical characteristics of the HUD and the aircraft canopy. There are several optical parameters that can affect target acquisition and aiming accuracy that involve the canopy, the HUD, and interactions between the two. The primary parameter that affects aiming accuracy is angular deviation due to the windscreen and/or the HUD. This angular deviation is manifested as pointing error (prism effects), collimation errors (lens effects associated with vergence, focus, parallax problems) and distortion (higher order aberration effects). In addition, other windscreen optical parameters may affect target acquisition, such as light transmission, and polarization. This paper describes these parameters and the techniques used to measure them.

Task, H. L. (1995). **Validation of a device and method for measuring aircraft transparency crazing.** *SAFE*, 26(1), 19-28.

A device was developed to measure the severity of aircraft transparency crazing with respect to the effect of crazing on vision through the transparency. Three studies were conducted to validate a vision contrast reduction model related to the visual effects of the veiling luminance. The first experiment used crazed aircraft cabin windows and demonstrated correlations between scene luminance and veiling luminances predicted by the model but resulted in higher than expected calculated contrast thresholds for human vision. The second experiment used a uniform light box to vary veiling luminance level to investigate the effects of masking due to the structure of the craze pattern on the cabin windows. The results of the second experiment agreed well with the derived model ($r = 0.998$ and $r = 0.999$) and had contrast thresholds more in line with previous studies. The third study tested a quality metric derived from the model designed to provide a subjective quality index related to the severity of crazing. The quality metric correlated well with subject's estimate of quality ($r = 0.981$). The overall results of all three experiments support the validity of the craze meter as a means of assessing the severity of crazing, with respect to visual effects in aircraft transparencies.

Task, H. L. (1988). ***Vision through aircraft transparencies.*** (NTIS Report No. AGARD-LS-156). AGARD Lecture Series 156. Visual Effects in the High Performance Aircraft Cockpit, 4-1 to 4-14. (DTIC No. ADA199306)

The primary purpose of this paper is to discuss, in detail, the optical and visual effects of aircraft transparencies including windscreens, canopies, Head-Up Display (HUD) combiners, and visors. The majority of the paper will treat aircraft windscreens and canopies with primary emphasis on high performance aircraft.

Task, H. L., Eggleston, R. G., & Genco, L. V. (1980). **A new angular deviation measurement device for aircraft transparencies.** *Proceedings of the Conference on Aerospace Transparencies* (pp. 141-147). London: Society of British Aerospace Companies Ltd.

An opto-electronic angular deviation measurement device incorporating a CCD array, which offers accuracy, repeatability and ease of operation while occupying a much smaller volume than long-throw laser devices of comparable performance, is described. The instrument's resolution is 0.07 mrad, and F-16 windscreen measurements have been found to compare favorably with data produced by alternative techniques. The device is to be used in characterizing distortion levels in such transparency-incorporating systems as Head-Up Displays.

Task, H. L., & Genco, L. V. (1985). ***The measurement of aircraft windscreen haze and its effect on visual performance.*** (Report No. AFAMRL TR-85-016). Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Laboratory. (DTIC No. ADA154949)

A new method of measuring haze in installed aircraft transparencies is developed and explained. Using data obtained with the new method, equations were derived to help predict target detection performance as it is affected by windscreen haze, windscreen transmissivity, ambient illumination, mean target luminance, target contrast and target size. The equations may be applied to many transparency types and configurations. Graphs are provided to show the effects of a number of typical visibility conditions. No similar relationships were found for older methods of measuring haze.

Task, H. L., & Merkel, H. S. (1989). ***A new method for measuring the transmissivity of aircraft transparencies.*** (Report No. AAMRL TR-89-044). Wright-Patterson AFB, OH: Armstrong Aerospace Medical Research Laboratory. (DTIC No. ADA216953)

The transmissivity of aircraft transparencies is currently measured following the American Standard for Testing and Materials Test Method D-1003. This method, originally intended for the measurement of small, thin, flat parts, has several shortcomings for measuring aircraft transparencies. A new method for measuring transmissivity, which overcomes the shortcomings of D-1003, is described. The precision of both methods was determined in laboratory tests; the results of these tests are presented. The new test method, in addition to its application advantages, is slightly more precise than ASTM D-1003.

Task, H. L., & Riegler, J., & Goodyear, C. (1999). **Effects of laser eye protection and aircraft windscreens on visual acuity through night vision goggles.** *Proceedings of the 37th Annual Symposium SAFE Association,* http://www.safeassociation.com

The combined use of hand-held laser pointers and night vision goggles (NVGs) is prevalent in nighttime tactical flight operations. Laser eye protection (LEP) is required during these missions to protect the eye from exposure to laser energy. The effects of the fielded FV-9 LEP visor and two prototype Wardove LEP spectacles on NVG-aided visual acuity (VA) were assessed. VA measurements were made through four types of aircraft transparencies using two different NVGs (4949C and 4949P) to determine if there were any interactions between the LEP, windscreens, and NVGs in their effects on VA. The results showed a correlation between the percent loss of NVG light due to the aircraft windscreens and the percent loss of NVG light due to the aircraft windscreens and the percent degradation in NVG VA (r-0.88). Also, the results revealed a small (8.5%), but statistically significant degradation in NVG-aided VA with the FV-9 LEP for both NVG models. Neither Wardove spectacle had a statistically significant effect on NVG-aided VA compared to the no-LEP condition.

Ward, F. E., DeFrances, A. J, & Eggleston, R. G. (1979). ***Development of a visual inspection technique (optical assessment of aircraft transparencies).*** (Report No. AFAMRL-TR-79-67). Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Laboratory. (DTIC No. ADA079369)

This work assessed the utility of different types of targets and psychophysical procedures for evaluating optical distortions induced by aircraft windscreens. Targets, both static and dynamic, were viewed through windscreens and the amount of distortion was judged by a magnitude estimation procedure. Judgments were analyzed by discriminant analysis to identify the targets that best facilitated good discrimination among windscreens. A psychophysical matching procedure was also evaluated. In some conditions, photographic representations of the distortion patterns were evaluated using the magnitude estimation procedures. The results of the work show that windscreen-induced distortion is a multidimensional attribute and is best evaluated by multiple inspection procedures. Specific static and dynamic targets are recommended for use in evaluating distortion. Correlations between physical measures of distortion and psychophysical judgments are reported as well as reliabilities for selected experiments. Suggestions for improvements and further work are included.

Welde, W. L. (1978). **The effects of windscreen distortion upon pilot approach and landing performance.** In R. E. Wittman (Ed.), *Conference on Aerospace Transparent Materials and Enclosures.* (Report No. AFFDL-TR-78-168, pp. 477-489). Wright-Patterson AFB, OH: Air Force Flight Dynamics Laboratory. (DTIC No. ADA065049)

A flight test was conducted with a modified NC-131 TIFS (Total In-Flight Simulator) aircraft to quantitatively assess the effect that various levels of windscreen distortion have upon pilot night approach and landing performance. Four highly qualified Air

Force C-131 pilots flew visual approaches and simulated landings under three experimental conditions of minimal, moderate, and severe windscreen distortion levels, and one baseline condition of zero distortion. The flight test was accomplished at Niagara Falls airport. The experimental task consisted of flying a head-down ILS instrument approach to a point two miles from the runway threshold, at which time the pilot transitioned to a night visual approach and simulated touchdown five feet above the runway. After training, each subject pilot performed five approaches with each of three specially fabricated distortion panels that were installed inside the evaluation cockpit, and a similar number of approaches under the no distortion condition. A repeated measures counterbalanced experimental design was employed to minimize the effects of learning and fatigue. Other intervening variables, such as turbulence and crosswind effects were controlled by utilizing the unique capabilities of the TIFS aircraft.

Task performance was assessed from 27 channels of digitally recorded flight parameter data. Pilot comments were also recorded at the conclusion of each approach. The results validated the findings of a parallel study conducted in a Boeing 727 visual simulator. The results indicated that as windscreen distortion increased, there was a degradation in task performance in the final touchdown phase with a definite break in performance occurring between the minimal and moderately distorted windscreen conditions. Distortion caused difficulty for the pilot to precisely determine his altitude above the runway or aircraft rate of descent, thus producing long and harder landings. Windscreen distortion was found to impact the vertical cues much more than the lateral cues required for runway alignment.

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BIBLIOGRAPHY OF ADDITIONAL AEROSPACE TRANSPARENCY RESEARCH

Beck, R. I., Koegeboehn, L. P., Lawrence, J. H., Jr., Murray, W. E., & Twomey, R. C. (1977). ***Standardized windshield fabrication specification.*** (Report No. AFFDL-TR-77-97). Wright-Patterson AFB, OH: Air Force Flight Dynamics Laboratory. (DTIC No. ADA080129)

The report documents the preparation of a laminated windshield transparency fabrication specification for a high performance military aircraft. The specification formatting and textual content are briefly discussed. The report utilizes an example document to present the standardized text required for structural, impact, temperature, anti-ice/de-fog, P-static and optical performance requirements and the pre-production and production testing requirements.

Bowman, D. R. (1998). ***Measurement of F-22 canopy expanded field angular deviation.*** (Report No. UDR-TR-1998-00004). Dayton, OH: University of Dayton Research Institute.

Brown, F. R., Crumley, L. M., & Alsher, D. (1954). ***The Development of inspection methods and criteria for optical distortion in cockpit enclosures part 1: A study of inspection methods for optical distortion in aircraft transparencies.*** (Report No. TED NAM AE-4405). Dept. of Navy Bureau of Aeronautics. (DTIC No. ADA38352)

A study has been made to determine the most practical method that will reliably reveal the visually significant variations in optical deviation in aircraft transparencies. The study has included a determination of the characteristics of the variations of deviation in transparencies that are most influential in rendering the transparencies objectionable to pilots.

Double aperture photography of a grid screen (1" x 1" squares) is proposed as the simplest and most reliable test to detect such variations of deviation. The proposed method requires that the picture be taken from a position closely approximating the position of the pilot's eyes in the cockpit in order to maintain geometric equivalence of the optical factors.

A tentative specification for the method of evaluating the photographs is proposed for validation of the basic technique. The method, the results of which correlate highly with pilot preference of tested windshields, considers as most significant the area of extent of distortion. It is recommended that the proposed method be validated and evaluated in a production situation.

Chiou, W. C. (1976). ***Visible and near infrared spectral transmission characteristics of windscreens in army aircraft.*** (Report No. USAARL 76-14). Fort Rucker, AL: U.S. Army Aeromedical Research Lab. (DTIC No. ADA022769)

The increasing application of electro-optical devices such as night vision goggles as aids in night flight demands a pre-requisite evaluation of the optical quality and the visual detection thresholds of those devices when they operate through the aircraft windscreen. This report presents an analysis of the spectral transmission characteristics from 360 to 1080 nm spectral range of sixteen Army aircraft windscreen samples. The samples were from six fixed-wing and seven rotary-wing aircraft windscreens.

Clark, B. A. J. (1972). **Consequences of tinting in aircraft windshields.** *American Industrial Hygiene Association Journal*, September 1972, 611-623.

Clark, B. A. J. (1979). **Veiling glare from spectacles and visors in aviation.** *Australian Journal of Optometry*, 62(6), 244-249.

Clark, B. A. J. (1971). **Vision loss from windshield tinting in a night visual flying accident.** *Aerospace Medicine*, 42(2), 190-195.

Clayton, K. I., West, B. S., & Bowman, D. R. (1985). ***Aircraft transparency test methodology.*** (Report No. AFWAL-TR-85-3125). Wright-Patterson AFB, OH: Flight Dynamics Laboratory. (DTIC No. ADA202922)

This program centered around a test matrix of 364 coupon type specimens to assess the degree of validity of the existing durability test methodology. Laboratory generated test data, for comparison to available in-service failure data, was produced from tests performed on specimens cut from the following actual transparency designs: F-16A coated monolithic polycarbonate canopy with the original production coating, manufactured by Texstar; F-16A laminated canopy, manufactured by Sierracin; F-15 monolithic stretched acrylic windshield, manufactured by Swedlow; F-15 monolithic stretched acrylic canopy, manufactured by Swedlow; and F-111 laminated ADBIRT windshield, manufactured by Sierracin. Various simulated environmental conditions were combined with the following test parameters: surface/chemical craze, haze/transmittance, high-rate impact, falling weight impact, coating adhesion, flatwise tension, torsional shear, wedge peel, thermal shock, in-flight abrasion, flight-line abrasion, and edge attachment. The durability evaluation of monolithic stretched acrylic, coated monolithic polycarbonate, and acrylic faced/polycarbonate laminated transparencies is highly dependent on a realistic accelerated weathering exposure. During this program, accelerated weathering was simulated using QUV, 120 degrees F, 7 hour UV/5 hour condensation cycles with 168 hours run time equaling one equivalent year of in-service exposure. The proposed accelerated weathering exposure alone appears too severe; the proposed accelerated weathering exposure combined with normal cleaning cycles appears to be representative of in-service usage.

Cocagne, C. J., & Blome, J. C. (1968, May). ***Optical requirements for high performance aircraft glass.*** Paper presented at the annual meeting of the American Ceramic Society.

Corney, N. S. (1973). **Optical requirements for aircraft transparencies.** In R. E. Wittman (Ed). *Conference on Aerospace Transparent Materials and Enclosures.* (Report No. AFML-TR-73-126). Wright-Patterson AFB, OH: Air Force Materials Laboratory. (DTIC No. ADA395461)

A paper given at the SBAC Symposium in London, June 1971, outlined the principles governing satisfactory vision through aircraft transparencies and summarized the methods in general use for evaluating the parameters associated with vision. The present paper reports progress in this field and invites comment on the work in hand.

The parameters, which have been established, are optical resolution, optical transmission, distortion, double imaging, minor scratches and inclusions, etc. These parameters must be assessed with the transparency mounted at the installed position relative to the user's eye position, and there should be no deterioration in quality when de-icing or de-misting equipment is in use.

For the guidance of designers, aircraft transparencies are allocated to broad categories according to the optical function of each. For example one category includes forward facing panels or areas thereof requiring very high precision, and another category includes side panels with less stringent requirements; in drawing up these categories no distinction has been made according to the materials of construction.

Current work in progress includes the allocation of limiting values of the parameters for satisfactory performance of transparencies of each of these categories. A number of methods for determining these parameters are being assessed prior to recommendation.

Problem areas associated with this work are highlighted e.g., that of quantifying the experience of pilots and observers, and that of determining the acceptable limits of the parameters consistent with the requirements of good performance and economy in fabrication and inspection.

Corney, N. S., & Shaw, W. (1971, June). **The specifications of optical requirements for aircraft transparencies.** *Proceedings of the Conference on Optical Transparencies* (pp. 19-34). London: Society of British Aerospace Companies Ltd. (DTIC No. ADD405089)

Crosley, J. K. (1968). ***Tinted windscreens in U. S. army aircraft.*** (Report No. USAARU 68-7). Fort Rucker, AL: U.S. Army Aeromedical Research Unit. (DTIC ADA667960)

Spectrophotometric analysis of visibility through tinted aircraft windshields.

Crumley, L. M. (1954). ***The development of inspection methods and criteria for optical distortion in cockpit enclosures. Part 2: Validation of an inspection test for WS distortion.*** (Report No. TED-NAM-AE-4405). Dept, Navy Bureau of Aeronautics Report. (DTIC No. AD046503)

In a previous study, an inspection test of aircraft windshield distortion was constructed so that it would agree in ordering windshields with a criterion of pilot judgments of the suitability of the windshields for use in aircraft on the basis of visual quality. The present cross-validation, with a selected set of windshields, indicates that the inspection test reliably predicts this criterion. Individual judges, using the inspection test, agree in relative scoring of windshields but disagree in overall level of scoring.

DeLuca, J. J. (1982). ***Effects of processing on the optical properties of a transparent polyurethane.*** Unpublished master's thesis, University of Massachusetts, Lowell, Massachusetts.

DeVilbiss, C. A., & Antonio, J. C. (1993). ***Comparative night vision goggle visual acuity measurements performed in the A-10 aircraft in an operational setting.*** (DTIC No. ADA266721).

The Night Vision Programs Office of the Aircrew Training Research Division, Armstrong Laboratory, responded to a request from the 422nd Operational Test Squadron at Nellis AFB to conduct the ground testing portion of their A-10 Night Vision Goggle (NVG) special project. Evaluations were conducted comparing the performance of four different NVGs under both laboratory and representative operational conditions. The performance of the F4949 "Super ANVIS" was superior to that of the other NVGs tested. Additionally, a comparative study was conducted evaluating the impact of two different windscreens on NVG image quality. The new windscreen allowed the transmission of more energy usable to the NVGs, thus enhancing image quality over that possible with the old windscreen.

Fisher, R. W. (1973). ***Correction of optical deviation in curved windshields.*** In R. E. Wittman (Ed.), Conference on Transparent Aircraft Enclosures. (Report No. AFML-TR-73-126, pp. 69-81). Wright-Patterson AFB, OH: Air Force Materials Laboratory. (DTIC No. ADA395461)

The desire to attain maximum aerodynamic qualities and low cockpit noise in two place fighter aircraft has necessitated development of thick conical windshields with short radii of curvature. This combination of thickness and curvature leads to optical deviation in the pilot's sight line even if the windshield is of perfect optical quality. This deviation can be as high as 10 milliradians, and obviously cannot be tolerated in future weapon systems that require visual target acquisition with accuracies of 1 milliradian or less. Another cause for concern is the fact that sight lines from each eye are deviated differently. While the eyes easily compensate for this with no loss in visual acuity, eye fatigue and false illusions of target motions may result.

This paper describes how optical deviations are theoretically charted using computer-graphic techniques and experimentally measured using a unique laser test apparatus. Theoretical results are compared to experimental measurements to show manufacturing errors in representative curved windshield assemblies. Various corrective techniques are studied including optical correction applied to either windshield or gun-sight, electronic correction to gun-sight, and geometric correction which establishes the optimum relationships between windshield radii, axis of curvature, and the pilot's nominal head-position. The corrective techniques are compared with respect to accuracy, limitations, and cost.

Foley, J. M. (1967). **Binocular disparity and perceived relative distance – an examination of two hypotheses.** *Vision Research*, 7, 655-670.

Gladwin, T. (1945). **Optical methods ferret transparent-plastic distortions.** *Aviation*, January 1945, 147-148; 254-256.

Glover, H. C. (1955). ***Light transmission and haze requirements for transparent enclosures.*** (Report No. WADC-TR-55-55). Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Laboratory. (DTIC No AD075479)

An analysis is made of the effects upon visibility induced by various transparencies through which aircrew members must perform the visual tasks of flying. Ranges of light transmission and haze values are established to define limits which are highly desirable, values acceptable if other factors take precedence, and minimum light transmission and maximum haze values which can be tolerated. The further reduction in light transmission induced by the angle of incidence of sloping windshields and its effect upon night visibility is evaluated.

Harris, J. S. (1978). ***Study and analysis of the rainbowing phenomenon existing in F-111 bird impact resistant transparencies.*** (Report No. UDR-TR-78-84). Dayton, OH: University of Dayton Research Institute.

Harris, J. S., Harding, K. G., & Mersch, S. H. (1980). **Techniques for evaluation of aircraft windscreen optical distortion.** *SPIE, Optics in Metrology and Quality Assurance*, (220), 56-70.

Holland, A. J. (1964). **The development of glass transparencies for modern aircraft.** *Aircraft Engineering,* (36), 403-405.

Holloway, R. A. (1970). ***Survey of optical test procedures for aircraft transparencies.*** (DTIC No. ADA997715)

Holloway, R. A. (1966). ***Windshield optical distortion and deviation – SST phase IIC.*** (DTIC No. ADA817938)

Irland, M. J. (1970, May). ***Windshield optics.*** (Report No. SAE -700480). Society of Automotive Engineers.

Kang, R. N., LaPage, C. S., Cora, S. R. (1996). ***Effect of haze in advanced laser eye protection visors on contrast acuity.*** (Report No. AL/OE-TR-1996-0002). Brooks AFB, TX: Armstrong Laboratory. (DTIC No. ADA304208)

Laboratory tests were conducted to evaluate the effects of haze in FV-6MR and FV-7 advanced laser eye protection (ALEP) visors on vision. Preliminary results from early operational assessment (EOA) flight tests with the FV-6MR (night use) and FV-7 (day use) visors suggested that the current USAF standards for haze may not adequately predict either the user acceptance or mission compatibility. In addition to the ALEP visors, the standard USAF sun and clear visors were also tested for comparison purposes. A contrast acuity test served as the measure of visual performance. The results suggest that the effects of haze in the ALEP visors on vision were primarily on low contrast targets, decreasing visual acuity. Presence of a glare source, simulating the sun near the line of sight, enhanced the effects of haze, further decreasing visual performance suggest that higher luminance transmittance mounted visors performed better. Overall, however, the results suggest that the ALEP visors and the standard USAF sun visor performed similarly, indicating that neither the dye technology used in ALEP visors nor the selective filtering of visual spectrum for laser protection is unique. It is recommended that the haze requirement for all ALEP visors not be relaxed from the current USAF helmet visor standard of 2.0%.

Kaufman, L. (1964). **On the nature of binocular disparity.** *American Journal of Psychology*, 77, 393-402.

Kay, B. F. (1979). ***Helicopter transparent enclosures volume I – design handbook.*** (Report No. USARTL-TR-78-25A). (DTIC No. ADA065268)

The Volume I design handbook is a comprehensive guide to the development of helicopter transparent enclosures. The handbook is structured in a manner that generally parallels the sequence of considerations used to develop helicopter transparencies. Separate chapters are devoted to subjects pertinent to the design, analysis and testing of transparent enclosures. Special characteristics and material properties are presented as applicable. Volume II is a general specification and contains design, development, and acceptance criteria. Guidelines for performing trade-offs between conflicting criteria are also given.

Kay, B. F. (1979). ***Helicopter transparent enclosures volume II - a general specification.*** (Report No. USARTL-TR-78-25B). (DTIC. No. ADA065462)

The Volume I design handbook is a comprehensive guide to the development of helicopter transparent enclosures. The handbook is structured in a manner that generally parallels the sequence of considerations used to develop helicopter

transparencies. Separate chapters are devoted to subjects pertinent to the design, analysis and testing of transparent enclosures. Special characteristics and material properties are presented as applicable. Volume II is a general specification and contains design, development, and acceptance criteria. Guidelines for performing trade-offs between conflicting criteria are also given.

Kay, M. E. (1950). ***Variation of deviation in transparent aircraft panels.*** (Report No. AF-TR-6003). Wright-Patterson AFB, OH: Air Material Command.

The maximum variations of deviation that can result in transparent aircraft sections, where the only test for optical efficiency is a deviation test, have been determined as functions of angle of incidence, thickness, radius of curvature, and distance over which the deviations are measured. It is shown that the deviation test is not adequate in determining the optical efficiency of transparent sections. Current specifications and methods of testing the optical quality of these sections are summarized and discussed. A fairly complete bibliography of reports, specifications, and other literature concerned with the optical quality of transparent sections is included. It is concluded that there is a need for additional research to determine the amount of variation of deviation that can be allowed without seriously interfering with the airman's visual efficiency, the distance over which this measurement should be made, and the best method of making these measurements.

Lazo, J. (1954). ***The development of inspection methods and criteria for optical distortion in cockpit enclosures. Part 3: Details of a proposed method for inspecting aircraft transparencies for visually objectionable distortion.*** (Report No. TED-NAM-AE-4405). Dept, Navy Bureau of Aeronautics Report. (DTIC No. AD046504)

The project authorized by reference DUAER letter AER-AE-59710, 22 Aug. 1950, requested that a study be made of methods for the inspection of aircraft transparencies for visually objectionable distortion. Laboratory studies of inspection methods considered most practicable for this purpose have been completed. The reports on Parts 1 and 2 of this project present the results of these studies. The details of the test method which the laboratory and analytical studies of Parts 1 and 2 indicated to be suitable have been developed and are presented with this report (Appendix A); reports of other methods and proposals which were considered during the preparation of this method are also listed (Appendix B).

Maher, E. F., & Wynn, R. E. (1975). ***The transmission, absorption coefficient, and index of refraction of the B-1 and FB-111 windscreens.*** (Report No. SAM TR-75-3). Brooks Air Force Base, TX: School of Aerospace Medicine. (DTIC No. ADA007040)

Spectral characteristics have been measured on the B-1, and two types of FB-111 windscreens in the spectral region of 0.3 - 0.2 um. The total transmission, index of refraction, dispersion and Lambert absorption coefficients were determined to quantitate the effective protection offered by these windscreens to high-intensity radiation. Total windscreen transmission measurements were performed

spectrophotometrically with each sample in normal incidence and adjacent to the detection aperture, allowing both the direct transmission and the forward scatter to be measured. The index of refraction for each windscreen was measured using a laser spectrometer system. The index of refraction at eight wavelengths in the visible spectrum was accurately determined with this system. Finally, a method is presented to calculate the light attenuation offered by three windscreens to this region of spectral radiation at various angles of incidence.

Marolo, S. A. (Ed.). (1976). ***Conference on aerospace transparent materials and enclosures, 18-21 November 1975, Atlanta, Georgia*.** (Report No. AFML-TR-76-54). Wright-Patterson AFB, OH: Air Force Materials Laboratory. (DTIC No. ADA032141)

The purpose of this report is to make available the technical papers presented at the Eleventh Conference on "Aerospace Transparent Materials and Enclosures". Thirty-nine technical papers are presented in seven sessions that address transparency design and performance, characterization, materials and processes, and bird impact resistance. The papers contained herein have been reproduced directly from the original manuscripts.

Marolo, S. A. (Ed.). (1983). ***Conference on aerospace transparent materials and enclosures held at Scottsdale, Arizona on 11-14 July 1983*.** (Report No. AFWAL/ML-TR-83-4154). Wright-Patterson AFB, OH: Air Force Materials Laboratory. (DTIC No. ADA140701)

Marolo, S. A. (Ed.). (1989). ***Conference on aerospace transparent materials and enclosures held in Monterey, California on 16-20 January 1989*.** (Report No. WRDC-TR-89-4044, Vol. 1). Wright-Patterson AFB, OH: Wright Research and Development Center. (DTIC No. ADA210488)

Marolo, S. A. (Ed.). (1989). ***Conference on aerospace transparent materials and enclosures (15th) 16-20 January 1989, Volume 2, Sessions 6 – 9.*** (Report No. WRDC-TR-89-4044, Vol. 2). Wright-Patterson AFB, OH: Wright Research and Development Center. (DTIC No. ADA210201)

Marolo, S. A. (Ed.). (1994). ***Conference on aerospace transparent materials and enclosures held in San Diego, California on 9 - 13 August 1993 Volume I.*** (Report No. WL/WP-TR-94-4084, Vol. 1). Wright-Patterson AFB, OH: Wright Laboratories. (DTIC No. ADA283925)

Marolo, S. A. (Ed.). (1994). ***Conference on aerospace transparent materials and enclosures held in San Diego, California on 9 - 13 January 1993 Volume 2 Sessions 5 - 9.*** (Report No. WL/WP-TR-94-4084, Vol. 2). Wright-Patterson AFB, OH: Wright Laboratories. (DTIC No. ADA283926)

Park, C. K., & Holly, F. F. (1975). ***The use of opaque louvers and shields to reduce reflections within the cockpit: A trigonometrical and plane geometrical approach.***

(Report No. USAARL 76-4). Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. (DTIC No. ADA017366)

Opaque shields can be used to channel light and thereby reduce reflections within the cockpit. These shielding devices range from the standard glare shield on top of the instrument panel to the more experimental use of Light Control Film and Micromesh for this purpose. Because of the need to determine the best position, width, spacing, etc. of these shielding devices, it was felt that a systematic approach would be highly desirable. This work describes a mathematical analysis to assess the applicability of those devices to resolve aircraft windscreen reflection problems.

Pinson, E. A., Chapanis, A. (1946). **Visual factors in the design of military aircraft.** *Aviation Medicine*, 17(2), 15-122.

Poehlmann, H. (1986). **A requiem for the aircraft canopy.** *Maintenance Magazine*, 11(3), 12-15.

Provines, W. F., & Kislin, B. (1971). **Transparencies used in military aviation and their effects on vision.** *Journal of the American Optometric Association*, 42(1), 57-63.

Provines, W. F., & Kislin, B. (1975). **Visual performance through a sample windshield segment of the B-1 aircraft.** *American Journal of Optometry and Physiological Optics*, 52, 51-57.

Provines, W. F., Kislin, B., & Tredici, T. J. (1977). ***Multiple images in the F/FB-111 aircraft windshield: their generation, spatial localization and recording.*** (Report No. SAM-TR-77-32). Brooks AFB, TX: USAF School of Aerospace Medicine. (DTIC No. ADA053470)

By reviewing basic laws of geometrical optics and applying some fundamentals of physiological optics, one can explain the generation and behavior of multiple images in the F/FB-111 windshield. The refinement of windshield optical laboratory techniques yields information for predicting and recording individual windshield multiple-image patterns.

Provines, W. F., Kislin, B., & Tredici, T. J. (1977). ***Optical evaluation of F/FB-111 field-service-test windshields.*** (Report No. SAM-TR-77-19). Brooks AFB, TX: USAF School of Aerospace Medicine. (DTIC No. ADA046490)

Ten shipsets (pairs) of F/FB-111 bird-impact-resistant windshields plus four shipsets of spares were optically evaluated in the USAF School of Aerospace Medicine (USAFSAM) Windshield Laboratory before installation into aircraft. This was in support of a field-test program directed by the Air Force Flight Dynamics Laboratory. To elicit distortion characteristics, the USAFSAM effort included the determination of light-transmissivity properties and haze values, prism-deviation mapping, and grid-

board photography. Seven of these windshields were optically evaluated also after the test, for pre versus post field-service direct comparison.

Aircraft transparencies are susceptible to numerous optical characteristics, which may impact the visual performance of the aircrew. These characteristics range in severity from simply distracting to hazardous. This report describes and illustrates the ten most common of these optical characteristics. It may be used as a guide by aircrews, maintenance personnel, and others working with transparencies to assist them in accurately identifying transparency optical defects.

Provines, W. F., Kislin, B., & Tredici, T. J. (1974). ***Proposed windshield for B-1 aircraft: an optical evaluation.*** (Report No. SAM-TR-74-35). Brooks AFB, TX: USAF School of Aerospace Medicine. (DTIC No. ADA001078)

A square sample segment, 25.4 cm by 25.4 cm (10 in. by 10 in.), representative of the B-1 aircraft proposed windshield was evaluated to determine if Air Force optical specifications would be met in the state-of-the-art production. The 3.53 cm thick (1.39 in.) five-layer laminate segment was composed of acrylic, silicone, polycarbonate, silicone, and polycarbonate layers, respectively. Light transmission was 66% in normal position and 54% when sloped to the corresponding installed angle (65 deg from normal). Deviation values, measured directly by displacement of a HeNe laser beam, varied from 0 to 7 min of arc when measured over the entire segment. A distortion map plotted at 2.54 cm (1 in.) intervals showed as much as a 3 min arc change per 2.54 cm. The haze value was 2.95%. Spectral transmission was acceptably flat between 300 and 900 nm, taken with a Cary spectrophotometer. The intensity of the first-order multiple image was 1.4% as bright as the primary image. These readings indicated that the segment failed to meet required specifications in distortion and deviation, but it was acceptable in all other respects.

Provines, W. F., Targove, B. D., & Kislin, B. (1973). ***Ghost imagery intensity and durability of selected anti-reflectant coatings.*** American Journal of Optometry and Archives of American Academy of Optometry, 50(1), 34-39.

Reed, R. H. (1972). ***Computer analysis of windshield multiple imaging.*** (DTIC No. 744044).

Robson, T. L., & Pinnell, W. R. (1994). **Optical evaluation of transparencies utilizing new test apparatus.** In S. A. Marolo (Ed.), *Conference on Aerospace Transparent Materials and Enclosures Volume II.* (Report No. WL-TR-94-4084, Vol. 2). Wright-Patterson AFB, OH: Wright Laboratory Material Command. (DTIC No. ADA283926)

An Optical Test Fixture (OTF) developed for WL/FIVR for evaluating directly formed and frameless transparencies at molding sites has been evaluated and will be utilized to determine optical quality of injection-molded transparencies. The OTF features an external collimated light source directed through a rotating test transparency. A computerized system synchronizes rotational position with televised

screen images of the light source, which has passed through the canopy. The light image position in captured screens is compared to an image without the transparency. Changes in the image position due to the transparency are utilized to calculate angular deviation in azimuth and elevation. Distribution of angular deviation can be obtained and displayed over large azimuth and elevation sweeps.

This paper includes a discussion of unique OTF features, mounting of transparencies and conduct of evaluation runs. Optical evaluation results for a control transparency are presented. OTF data are compared to results obtained utilizing another apparatus. The plan for using the OTF as an on site facility to optimize transparency direct forming processes is discussed.

Sjhaikh, N. (1991). ***Surface acoustic wave technique for craze detection and stress measurement of aircraft transparencies.*** (Report No. WRDC-TR-90-3082). Wright-Patterson AFB, OH: Flight Dynamics Directorate, Wright Laboratories. (DTIC No. ADA235943)

A nondestructive technique employing surface acoustic waves was developed for detecting and characterizing flaws and degradation in transparent enclosures of fighter aircraft. The focus of research has been measurement of craze and stresses in the acrylic top layer of laminated transparencies. The craze severely degrades the optical performance of the transparent enclosure and is one of the major causes of the limited service life. The stress accelerates the incipience of craze in addition to causing eventual fracture. The acoustic technique uses silicone rubber wedges to launch and receive surface acoustic waves. Both Rayleigh surface wave and critical angle longitudinal (L-cr) wave transducers were developed and produced favorable test results. L-cr waves are recommended for stress measurement and Rayleigh surface waves are recommended for craze detection. Further work is recommended for better resolution of crazes and application to stress measurement.

Smyth, C. (1977). ***Computing internal cockpit reflections of external point-light sources for the model 209 AH-1S helicopter flat-plate canopy design.*** (Report No. HEL-TM-20-77). U.S. Army Human Engineering Laboratory. (DTIC No. ADA043120)

The US Army Human Engineering Laboratory (HEL) has developed a computer program for computing the internal cockpit reflections of external point light sources. Computations have been completed for the Model 209 AH-1S COBRA helicopter with the flat-plate canopy design. The results indicate that internal reflections are possible for a wide range of external source locations. A computer graphics output is included in the program to show the reflection points on a perspective drawing of the cockpit canopy as seen from the pilot's position. This report contains hard copies of such perspectives and describes the program and routines.

Smyth, C. (1977). ***Computing internal cockpit reflections of external point light sources for the model YAH-64 advanced attack helicopter (low glare canopy design).*** (Report

No. HEL-TM-24-77). U.S. Army Human Engineering Laboratory. (DTIC No. ADA043367)

The US Army Human Engineering Laboratory (HEL) has developed a computer program for computing the internal cockpit reflections on the transparent canopy surfaces of external point light sources. Computations have been completed for the Model YAH-64 Advanced Attack Helicopter (low glare canopy design). The results show that primary reflections as seen from the pilot's position are possible on (1) the upper rear corners of the forward side canopy surfaces, (2) the upper edges of the rear sides, and (3) the sides of the top surface. Computations have also been completed for the copilot's position and show possible reflections on the front and side surfaces. A computer graphics output is used to show reflection points on canopy layouts and perspectives of the cockpit.

Smyth, C., & Stowell, H. R. (1979). ***The verification of a computer model of internal light reflections for helicopter canopy design.*** (Report No. HEL-TM-21-79). U.S. Army Human Engineering Laboratory. (DTIC No. ADA080473)

The US Army Human Engineering Laboratory (USAHEL) has experimentally verified a computer model for internal light reflections on the transparent surfaces of helicopter canopies. The model was verified using a mockup of the Model 209 AH-1S Helicopter with the flat plate canopy design. The transmittance and coordinates of the light images on the canopy surfaces were measured at various light source positions. A matched sample was computed for the source positions using the computer model. Pearson's correlation coefficients for a linear regression analysis for the matched measured and computed values are greater than 0.98, and the results are statistically significant at the .01 level.

Stamper, D. A., Lund, D. J., Levine, R. R., Molchany, J. W., & Best, P. (1986). ***Flash/crazing effects on simulator pursuit tracking performance.*** (Report No. LAIR-214). Letterman Army Institute of Research Presidio of San Francisco, CA. (DTIC No. ADA167689)

Day sights which are purposefully or inadvertently irradiated with laser radiation may become nonfunctional due to cracking or crazing of the optical glass. The degree of performance degradation may be related to the amount of damage to the glass and possible flash blindness from re-radiation. Thirty-two male enlisted men and officers tracked a scale model tank through a constant arc at a simulated distance of 1 km, using a laboratory constructed viscous-damped tracking device. There were four crazing groups (4 men/group) under bright and dim ambient light conditions for a total of eight groups. Each man tracked the target during three flash/crazing and three crazing only trials, which were randomly presented during 30 trials. The simulated countermeasure which included the flash and crazing had dramatic effects on tracking performance, even under daylight conditions. Under the most severe degree of crazing, tracking performance was not possible under either ambient light condition. The relatively small amounts of laser radiation used to craze the BK-7 glass used in

this study, which led to significant performance decrements, demonstrates the potential impact of flash/crazing effects on operators of day sights.

Stowell, H. R., & Smyth, C. C. (1977). ***Investigation of inside light reflection problem on the flat plate canopy (FPC) for model 209 AH-1S helicopter.*** (Report No. HEL-TM-13-77). U.S. Army Human Engineering Laboratory. (DTIC No. ADA041332)

Various approaches were examined for a possible solution to the light-reflection problem inside the Model 209 AH-IS helicopter cockpit with the flat-plate canopy (FPC). A computer program was developed to identify primary light reflections inside the FPC at the pilot's eye position. Modifying the side panels on the FPC with curved surfaces may be the only satisfactory solution to the inside light-reflection problem.

Taboada, J. (1977). ***Lateral shearing interferometric technique for transparency analysis.*** Applied Optics, 16: 2603-2604.

Taboada, J. (1981). ***Optical distortion analyzer system.*** (DTIC No. ADD009492)

Taboada, J., & Duelm, A. J. (1978). ***Shearing interferometer with scanned photodiode array and microcomputer for automatic transparency distortion measurements.*** (DTIC No. ADD306659)

Wentworth, S. L., McGowin, E., Ivey, R. H., Rash, C. E., & McLean, W. E. (1995). ***Transmittance characteristics of U.S. army rotary-wing aircraft transparencies.*** (Report No. USAARL 95-19). Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. (DTIC No. ADA295035)

This report documents a survey of the spectral and luminous transmittance characteristics of transparencies (windscreens) used in currently fielded U.S. Army rotary-wing aircraft. The survey was conducted in two phases. In the first phase, samples of windscreens from each aircraft type were evaluated in the laboratory for photopic (day) and scotopic (night) luminous transmittance. The spectral transmittance of each sample also was measured. Based on laboratory measurements of unused samples, all windscreens met specifications. However, field measurements on windscreens showed consistent failure of luminous transmittance requirements. This loss of transmittance is attributed to haze resulting from exposure to environmental factors.

Wildes, R. P. (1991). **Direct recovery of three-dimensional scene geometry from binocular stereo disparity.** *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 13(8): 761-774.

Wiser, G. L. (1971). **Transparency applications of polycarbonates.** *Aircraft Engineering*, 43.

Wittman, R. E. (Ed.). (1978). ***Conference on aerospace transparent materials and enclosures.*** (Report No. AFFDL-TR-78-168). Wright-Patterson AFB, OH: Air Force Flight Dynamics Laboratory. (DTIC No. ADA065049)

The purpose of this report is to make available the technical papers presented at the Twelfth Conference on "Aerospace Transparent Materials and Enclosures". Thirty-eight technical papers are presented in seven sessions that address transparency design and performance, characterization, materials and processes, and bird impact resistance. The papers contained herein have been reproduced directly from the original manuscripts.

Wittman, R. E. (Ed.). (1973). ***Conference on transparent aircraft enclosures.*** (Report No. AFML-TR-73-126). Wright-Patterson AFB, OH: Air Force Materials Laboratory. (DTIC No. ADA395461)

The purpose of this report is to make available the technical papers presented at the Tenth Conference on "Transparent Aircraft Enclosures". This conference was held for the exchange of knowledge on new developments and design concepts concerned with vision areas of crew enclosures. Also to make known the state-of-the-art with respect to transparent plastics, interlayer materials, and glass, of the type suitable for these applications. The papers contained herein have been reproduced directly from the original manuscripts.

Wittman, R. E. (Ed.). (1965). ***Transparent materials for aerospace enclosures.*** (Report No. AFML-TR-65-212). Wright-Patterson AFB, OH: Air Force Materials Laboratory. (DTIC No. AD0473543)

Considering the tradeoffs that have had to be made, we believe that the designers of windshields and windows have been quite successful in maintaining good vision for flight personnel. The factors that can seriously degrade vision are transmission loss, contrast loss, image distortion, and obstruction by structural supports. For very specialized applications, vision can be improved by proper filters added to windows.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM) STANDARDIZED TEST METHODS AND PRACTICES BIBLIOGRAPHY

ASTM D 1003-00: **Standard test method for haze and luminous transmittance of transparent plastics.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM E 167-96: **Standard practice for goniophotometry of objects and materials.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 319-91a: **Standard practice for polarized light detection of flaws in aerospace transparency heating elements.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 320-94: **Standard test method for hail impact resistance of aerospace transparent enclosures.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 330-89: **Standard test method for bird impact testing of aerospace transparent enclosures.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 428-01: **Standard test method for intensity of scratches on aerospace glass enclosures.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 484-02: **Standard test method for stress crazing of acrylic plastics in contact with liquid or semi-liquid compounds.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 520-97: **Standard test method for environmental resistance of aerospace transparencies.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 521-83: **Standard test method for bond integrity of transparency laminates.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 548-01: **Standard test method for intensity of scratches on aerospace transparent plastics.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 733-90: **Standard practice for optical distortion and deviation of transparent parts using the double-exposure method.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 734-95: **Standard test method for shear strength of fusion bonded polycarbonate aerospace glazing material.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 735-94: **Standard test method for abrasion resistance of transparent plastics and coatings using the oscillating sand method.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 736-95: **Standard test method for impact resistance of monolithic polycarbonate sheet by means of a falling weight.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 790-02: **Standard guide for testing materials for aerospace plastic transparent enclosures.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 791-96: **Standard test method for stress crazing of transparent plastics.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 801-96: **Standard test method for measuring optical angular deviation of transparent parts.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 942-02: **Standard guide for selection of test methods for interlayer materials for aerospace transparent enclosures.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 1164-97: **Standard test method for evaluation of transparent plastics exposed to accelerated weathering combined with biaxial stress.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 1165-98: **Standard test method for measuring angular displacement of multiple images in transparent parts.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 1181-96: **Standard test method for measuring binocular disparity in transparent parts.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 1252-89: **Standard test method for measuring optical reflectivity of transparent materials.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 1316-90: **Standard test method for measuring the transmissivity of transparent parts.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 1362-97: **Standard test method for shear strength and shear modulus of aerospace glazing interlayer materials.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 1863-98: **Standard test method for measuring the night vision goggle-weighted transmissivity of transparent parts.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 1864-98: **Standard test method for dust erosion resistance of optical and infrared transparent materials and coatings.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 2108-01: **Standard practice for inspection of transparent parts by prism.** West Conshohocken, PA: American Society for Testing and Materials.

ASTM F 2156-01: **Standard test method for measuring optical distortion in transparent parts using grid line slope.** West Conshohocken, PA: American Society for Testing and Materials.

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HUMAN ENGINEERING DIVISION
AEROSPACE TRANSPARENCY-RELATED PATENTS

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United States Patent [19]

Task

[11] **4,249,823**

[45] **Feb. 10, 1981**

[54] **WINDSCREEN ANGULAR DEVIATION MEASUREMENT DEVICE**

[75] Inventor: Harry L. Task, Dayton, Ohio

[73] Assignee: The United States of America as represented by the Secretary of the Air Force, Washington, D.C.

[21] Appl. No.: 85,453

[22] Filed: Oct. 16, 1979

[51] Int. Cl.^{3} G01N 21/41

[52] U.S. Cl. .... 356/128; 250/237 G; 356/239

[58] Field of Search .... 356/239, 128–137, 356/399–401; 250/237 G

[56] References Cited

U.S. PATENT DOCUMENTS

3,688,235 8/1972 Migeotte 356/239

Primary Examiner—John K. Corbin

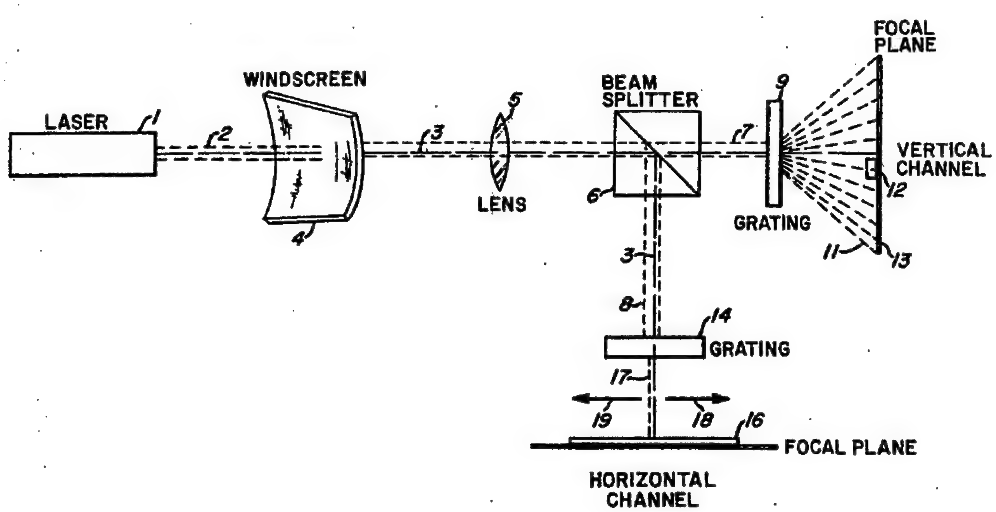
Assistant Examiner—Bruce Y. Arnold

Attorney, Agent, or Firm—Donald J. Singer; Casimer K. Salys

[57] **ABSTRACT**

An apparatus for detecting the angular deviation from an axis imparted to a ray when passing through a transparent medium, for resolving the angular deviation into its components, and for generating electrical signals accurately representing the magnitudes of such components. A laser beam is projected along an optical axis through the medium and focussed by a displacement compensation lens. The beam is divided into channels with a beam splitter, each channel being incident upon a transmission diffraction grating. Each grating, characterized by fine parallel lines of substantially random size and spacing, generates a fan-shaped region of luminous energy. At a distance equal to the focal length of the lens, the fan-shaped regions cross detector arrays aligned parallel to the grating lines. A change in the angular deviation proportionally translates the crossing point along the detector array.

7 Claims, 4 Drawing Figures



United States Patent [19]

Task et al.

[11] **4,257,164**

[45] **Mar. 24, 1981**

[54] **OPTICAL PROTRACTOR**

[75] Inventors: **Harry L. Task**, Dayton; **Ross J. Gafvert**, Enon, both of Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **959,050**

[22] Filed: **Nov. 9, 1978**

[51] **Int. Cl.**[3] **G01B 11/26**

[52] **U.S. Cl.** .... **33/1 N; 350/112; 356/138; 356/247**

[58] **Field of Search** .... 33/1 N; 356/138, 247; 350/112

[56] **References Cited**

U.S. PATENT DOCUMENTS

3,463,593 8/1969 Horan 356/142

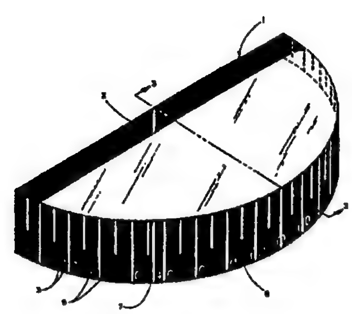
Primary Examiner—William D. Martin, Jr.

Attorney, Agent, or Firm—Joseph E. Rusz; Casimer K. Salys

[57] **ABSTRACT**

An optical device for measuring the angles formed between a line-of-sight and the normal to a planar surface intersected thereby. A solid piece of optically transparent material having a relatively large index of refraction is geometrically shaped to have a planar base surface, with a reference mark theron, and a curvilinear viewing surface with scale marks to designate angular orientations. The exterior surfaces are optically polished to create mirrored surfaces for internal reflection. To accentuate contrast, the planar surface containing the reference mark is coated with a layer of contrasting opaque material. Angles are measured by placing the planar base surface of the device on the planar surface intersected by the line-of-sight and aligning the reference mark with the point of intersection. When viewed from the observation point defining the line-of-sight, an image of the reference mark appears on the scaled surface at a location representing the line-of-sight angle.

10 Claims, 10 Drawing Figures



United States Patent [19]

Task

[11] **4,299,482**

[45] **Nov. 10, 1981**

[54] **MEASUREMENT OF WINDSCREEN DISTORTION USING OPTICAL DIFFRACTION**

[75] Inventor: Harry L. Task, Montgomery County, Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **90,383**

[22] Filed: **Nov. 1, 1979**

[51] **Int. Cl.**³ **G01B 9/00**

[52] **U.S. Cl.** **356/124**

[58] **Field of Search** .... 356/124, 125, 347; 350/162 R, 162 SF

[56] **References Cited**

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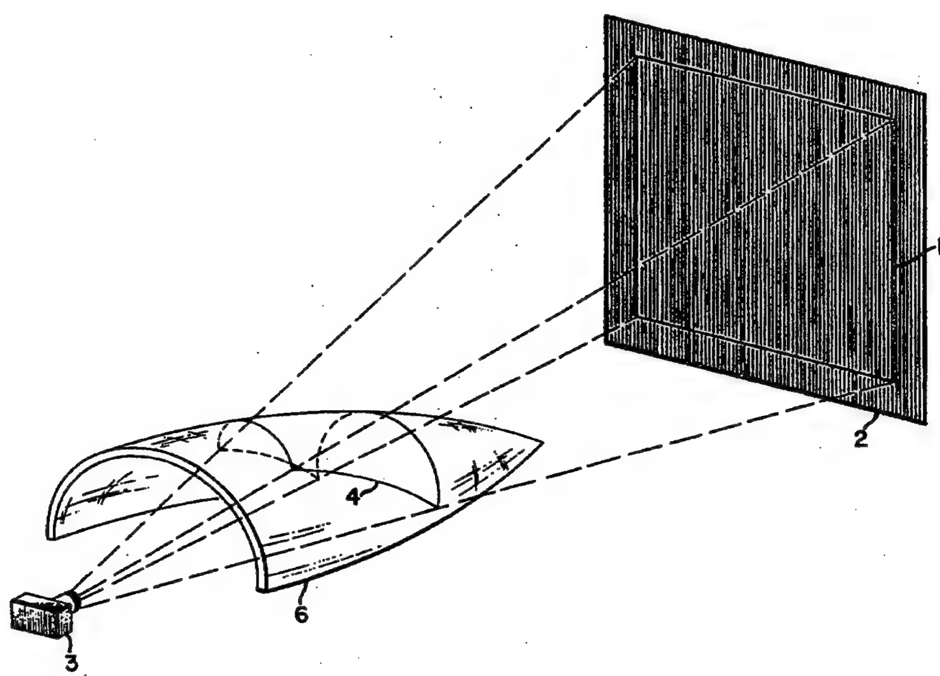
Heiling, G. M., and L. T. Lemke, "Lens Magnification Measuring System", IBM Technical Disclosure Bulletin, vol. 14, No. 5, Oct. 1971.

Primary Examiner—Conrad J. Clark
Attorney, Agent, or Firm—Donald J. Singer; Casimer K. Salys

[57] **ABSTRACT**

A measurement apparatus and method for detecting, resolving and quantifying the distortion caused by a relatively large region of a distorting optically transparent medium. A precisely defined pattern is viewed through the transparent medium to introduce the distortion effects. The altered pattern is photographically recorded in thin film transparency format. A beam of coherent luminous energy projected through the transparency, once focused, produces a Fraunhofer diffraction pattern which is the Fourier transform of the original pattern. Conventional distortion characteristics in the Fourier domain appear in a form more amenable to quantification and analysis. The character and magnitude of the distortion is readily ascertained by comparing the transforms of distorted and undistorted patterns, yielding quantitative data comparable to conventional distortion effects in terms of grid line slop and lens factor.

4 Claims, 7 Drawing Figures



United States Patent [19]

Genco et al.

[11] **4,310,242**

[45] **Jan. 12, 1982**

[54] **FIELD TEST UNIT FOR WINDSCREEN OPTICAL EVALUATION**

[75] Inventors: **Louis V. Genco**, Enon; **Harry L. Task**, Montgomery County, both of Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **136,210**

[22] Filed: **Apr. 1, 1980**

[51] **Int. Cl.**^{3} **G01N 21/41**

[52] **U.S. Cl.** **356/128**; 356/239; 356/365

[58] **Field of Search** 356/32, 33, 365, 121, 356/124, 124.5, 128, 239

[56] **References Cited**

U.S. PATENT DOCUMENTS

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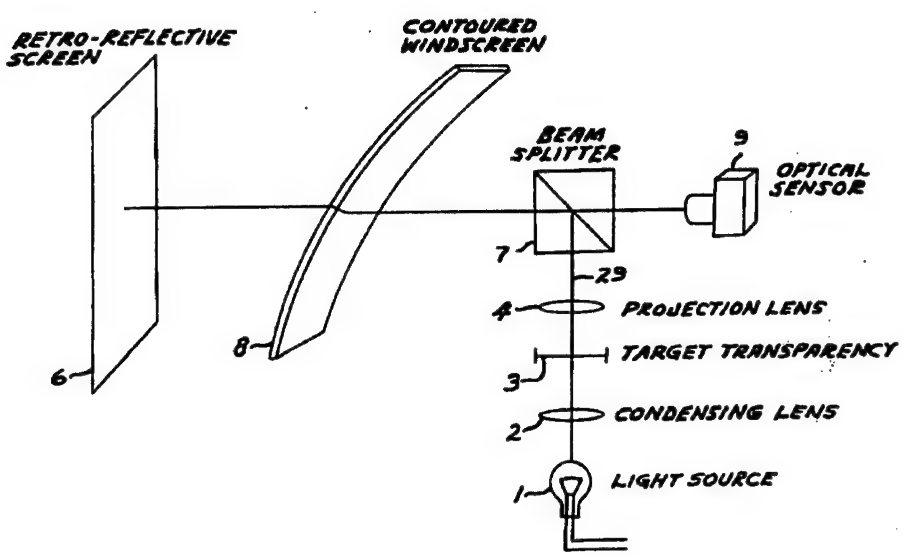
Consortini et al., "Investigation of Atmospheric Turbulence by Narrow Laser Beams", Applied Optics, vol. 9, No. 11, (Nov. 1970), pp. 2543–2547.

Primary Examiner—R. A. Rosenberger
Attorney, Agent, or Firm—Donald J. Singer; Casimer K. Salys

[57] **ABSTRACT**

An apparatus for analyzing the deleterious characteristics of optically transparent bodies, including distortion, multiple imaging and birefringence. A beam of light is projected along an optical axis onto a beam splitter. The reflected segment passes through the transparent body and is then reflected back along nearly the same path toward the beam splitter by a retro-reflective screen lying at the image plane of the beam. The portion of the reflected beam passing directly through the beam splitter is detected by an optical sensor in substantial orientation with the axis of the beam reaching it. Distortions and multiple imaging are detected by shape changes and images, respectively, in a pattern of opaque areas superimposed on the originating beam. Birefringence is analyzed by polarizing the originating beam and observing the color pattern and intensity reaching the sensor.

6 Claims, 8 Drawing Figures



United States Patent [19]

Task et al.

[11] **4,377,341**

[45] **Mar. 22, 1983**

[54] **SYSTEM FOR MEASURING ANGULAR DEVIATION IN A TRANSPARENCY**

[75] Inventors: **Harry L. Task**, Dayton; **Louis V. Genco**, Enon; **Kenneth L. Smith**; **Albert G. Dabbs**, both of Dayton, all of Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **242,816**

[22] Filed: **Mar. 11, 1981**

[51] **Int. Cl.**^{3} **G01N 21/88**

[52] **U.S. Cl.** **356/239**; 356/371

[58] **Field of Search** 356/239, 371, 430, 431; 250/562, 572

[56] **References Cited**

U.S. PATENT DOCUMENTS

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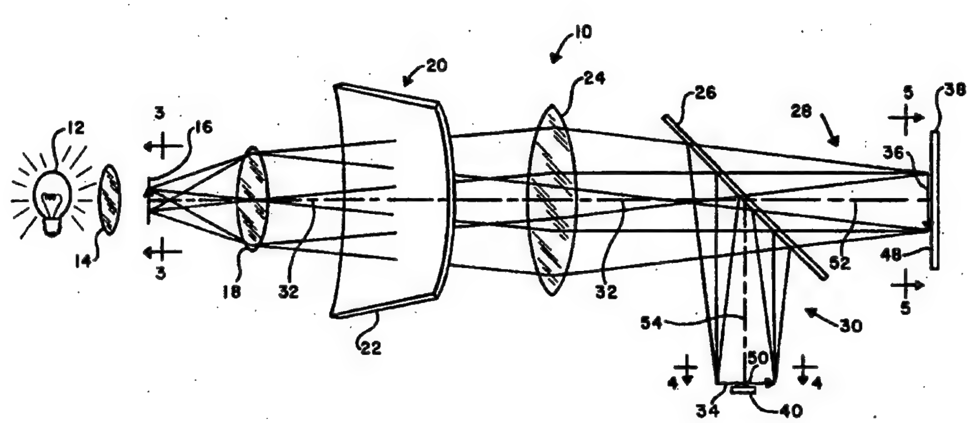
4,249,823	2/1981	Task	356/128
4,255,055	3/1981	Schave	356/239 X
4,310,242	1/1982	Genco et al.	356/239 X

Primary Examiner—John K. Corbin
Assistant Examiner—Matthew W. Koren
Attorney, Agent, or Firm—Donald J. Singer; John R. Flanagan

[57] **ABSTRACT**

An improved system for measuring absolute angular deviation through transparencies, such as aircraft windscreens, uses an incoherent light source and a target configuration in the form of an opaque slide with a transparent "L"-shaped pattern. The positions of images of the legs of the "L" passed through the transparency are detected by CCD arrays for measurement of the azimuth and elevation components of angular deviation for each tested point on the transparency, uncontaminated by lateral displacement errors.

6 Claims, 6 Drawing Figures



United States Patent [19]

Task

[11] **4,398,822**

[45] **Aug. 16, 1983**

[54] **TWO-AXIS ANGULAR DEVIATION MEASUREMENT SYSTEM WITH TARGET IMAGE ROTATING MEANS**

[76] Inventor: **Harry L. Task**, 5513 Snowbank Cir., Dayton, Ohio 45431

[21] Appl. No.: **327,301**

[22] Filed: **Dec. 3, 1981**

[51] **Int. Cl.**³ **G01N 21/88**

[52] **U.S. Cl.** **356/239**; 356/371

[58] **Field of Search** 356/239, 371, 430, 431; 250/562, 572

[56] **References Cited**

U.S. PATENT DOCUMENTS

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3,688,235	8/1972	Migeotte	356/239
4,249,823	2/1981	Task	356/128
4,310,242	1/1982	Genco et al.	356/239 X
4,377,341	3/1983	Task et al.	356/239

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Genco, Louis V. and Task, Harry L., "Aircraft Transparency Optical Quality: New Methods of Measurement", Feb. 1981, Report No. AFAMRL-TR-81-21, pp. 8-19.

Primary Examiner—John K. Corbin

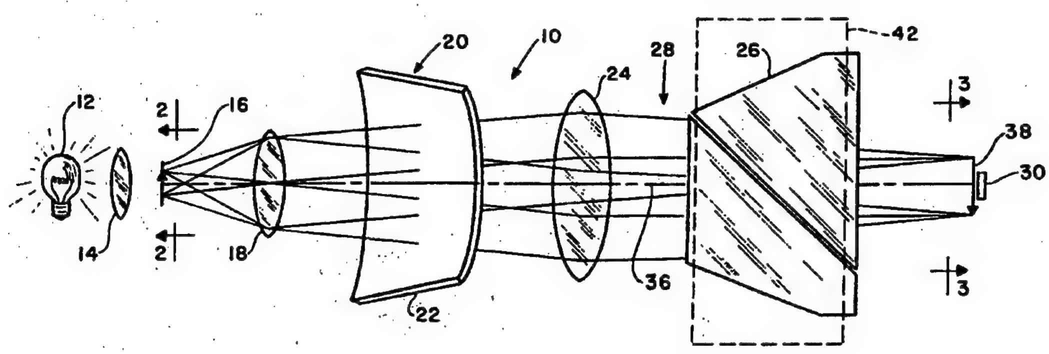
Assistant Examiner—Matthew W. Koren

Attorney, Agent, or Firm—Donald J. Singer; John R. Flanagan

[57] **ABSTRACT**

An improved system for measuring absolute angular deviation through transparencies, such as aircraft windscreens, uses an incoherent light source and a target configuration in the form of an opaque slide with a transparent "L"-shaped pattern. The positions of images of the legs of the "L" after passing through the transparency are detected at separate times by a single CCD array through rotation of the image of the "L"-shaped pattern ninety degrees by rotation of a Pechan prism about the optical axis of the system. In such manner, horizontal (azimuth) and vertical (elevation) components of angular deviations is measured for each tested point on the transparency, uncontaminated by lateral displacement errors.

4 Claims, 4 Drawing Figures



United States Patent [19]

Task et al.

[11] **Patent Number: 4,461,570**

[45] **Date of Patent: Jul. 24, 1984**

[54] **METHOD FOR DYNAMICALLY RECORDING DISTORTION IN A TRANSPARENCY**

[75] Inventors: **Harry L. Task**, Dayton; **Louis V. Genco**, Enon, both of Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **386,488**

[22] Filed: **Jun. 9, 1982**

[51] **Int. Cl.**^{3} **G01N 21/00**
[52] **U.S. Cl.** **356/239**; 356/389
[58] **Field of Search** 356/124, 127, 389, 398, 356/239, 240, 371

[56] **References Cited**

U.S. PATENT DOCUMENTS

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4,299,482	11/1981	Task	356/124

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1407812	9/1975	United Kingdom .	

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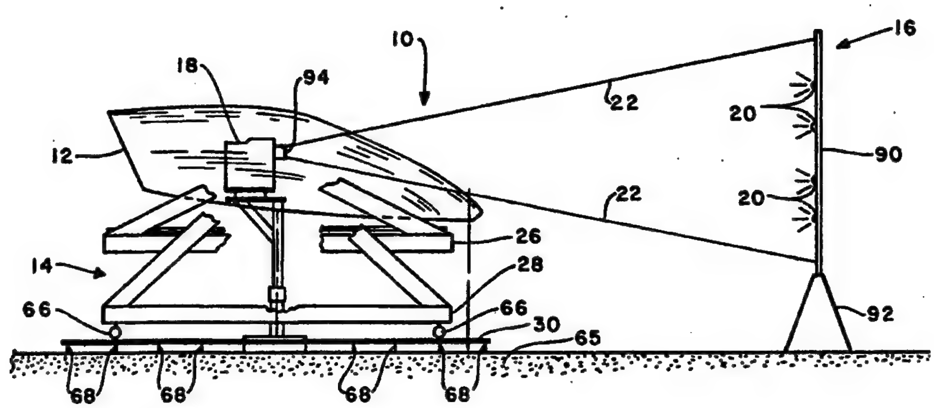
Genco, Louis V. and Task, Harry L., "Aircraft Transparency Optical Quality: New Methods of Measurement," Feb. 1981, Report No. AFAMRL-TR-81-21.
Self, Hershel C. and Task, Harry L., "Potential of Optical Analysis for Measuring Windscreen Distortion," Dec. 1980, Report No. AFAMRL-TR-80-104.

Primary Examiner—William L. Sikes
Assistant Examiner—Matthew W. Koren
Attorney, Agent, or Firm—Donald J. Singer; John R. Flanagan

[57] **ABSTRACT**

A method for dynamically recording distortion in a transparency includes a support fixture for mounting the transparency for movement about a predetermined horizontal or vertical axis, with a camera disposed in back of the transparency while a test target is disposed in front of it. The test target has a plurality of small light sources arranged in a rectangular matrix pattern toward which the camera is aimed through the transparency. By opening the camera shutter for a period of time as the transparency is moved through a predetermined angle, a photographic record of distortion at a plurality of regions in the transparency is produced.

6 Claims, 7 Drawing Figures



United States Statutory Invention Registration [19]

Task

[11] **Reg. Number:** **H139**

[43] **Published:** **Oct. 7, 1986**

[54] **REMOVABLE CLEANABLE ANTIREFLECTION SHIELD**

[75] Inventor: **Harry L. Task**, Watertown, Mass.

[73] Assignee: **The United States of America as reperesented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **690,212**

[22] Filed: **Jan. 10, 1985**

[51] **Int. Cl.⁴** **B64D 45/00; B60J 3/00**

[52] **U.S. Cl.** .... **244/121; 296/97 C**

[58] **Field of Search** .... 244/121; 296/97 R, 97 C

[56] **References Cited**

U.S. PATENT DOCUMENTS

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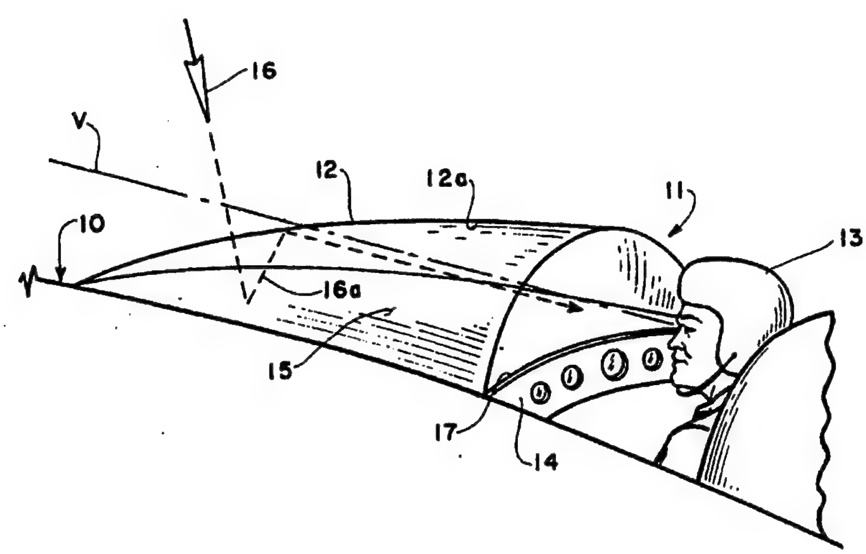
4,005,899	2/1977	Rigney	296/97 E
4,065,171	12/1977	Nagy	296/97 E
4,399,347	8/1983	Schmitt	219/203
4,449,747	5/1984	Morgan et al.	296/97

Primary Examiner—Deborah L. Kyle
Assistant Examiner—Michael J. Carone
Attorney, Agent, or Firm—Donald J. Singer; Bobby D. Scearce

[57] ABSTRACT

A replaceable anti-reflection shield for the glare surface beneath the windscreen of a vehicle is described which comprises a flexible panel of light absorbing material, such as black cloth, velvet, canvas or plastic, of size and configuration corresponding to that of the glare surface for placement on and conformance to the contour of the glare surface beneath the windscreen, and peripheral attaching means such as adhesive strips, snaps, Velcro® strips, suction cups, or similar devices, on the flexible panel for detachably securing the peripheral edges of the panel to the glare surface, whereby the panel is easily removed for cleaning or replacement.

5 Claims, 3 Drawing Figures



United States Patent [19]

Task et al.

[11] **Patent Number: 4,623,258**

[45] **Date of Patent: Nov. 18, 1986**

[54] **METHOD FOR MEASURING HAZE IN TRANSPARENCIES**

[75] Inventors: **Harry L. Task**, Dayton; **Louis V. Genco**, Enon, both of Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **623,667**

[22] Filed: **Jun. 22, 1984**

[51] **Int. Cl.**[4] **G01N 21/01**

[52] **U.S. Cl.** **356/432**

[58] **Field of Search** 356/337, 338, 340, 342, 356/445, 446, 447, 448, 215, 221, 236; 250/562, 572

[56] **References Cited**

U.S. PATENT DOCUMENTS

3,639,112	2/1972	Poola	65/29
3,737,665	6/1973	Nagae	250/219 DF
4,310,242	1/1982	Genco et al.	356/128
4,400,089	8/1983	Farabaugh	356/382

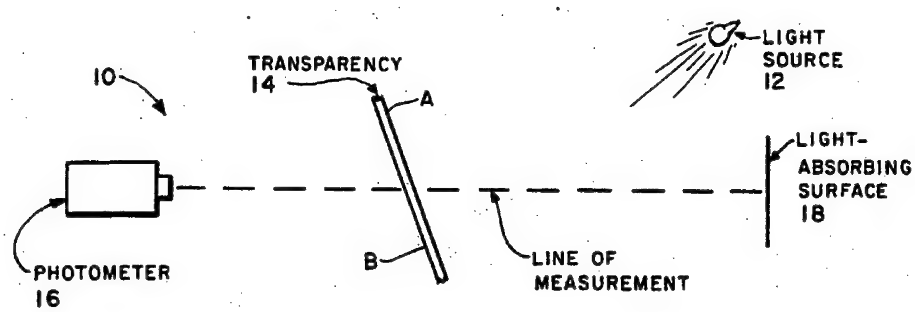
Primary Examiner—Bruce Y. Arnold

Attorney, Agent, or Firm—Bobby D. Scearce; Donald J. Singer; John R. Flanagan

[57] **ABSTRACT**

A method of measuring haze in a transparency includes the steps of illuminating a transparency to be measured from one side using a semi-collimated light source disposed in a predetermined angular relationship to the transparency, measuring the illumination (E) falling on a surface of the transparency from the one side thereof, then along a predetermined line of measurement through the transparency using a photometer to measure the veiling luminance (L) within the transparency from another side of the transparency opposite to the one side thereof, and, finally, calculating the haze index of the transparency by solving $H_i=L/E$.

10 Claims, 4 Drawing Figures



United States Statutory Invention Registration [19]

[11] **Reg. Number:** **H315**

[43] **Published:** **Aug. 4, 1987**

Genco et al.

[54] **METHOD OF MEASURING OPTICAL PROPERTIES OF A TRANSPARENCY**

[75] Inventors: **Louis V. Genco**, Enon; **Harry L. Task**, Dayton, both of Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force, Washington, D.C.**

[21] Appl. No.: **607,090**

[22] Filed: **May 4, 1984**

[51] **Int. Cl.**[4] **G01B 9/00**

[52] **U.S. Cl.** **356/125; 356/127**

[58] **Field of Search** 356/125, 126, 127; 358/107, 108

[56] **References Cited**

U.S. PATENT DOCUMENTS

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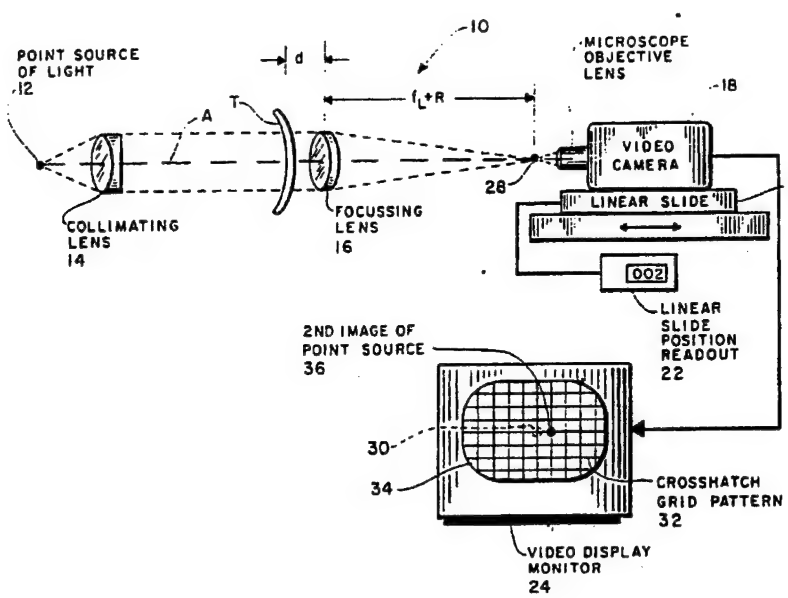
3,981,589	9/1976	Spitzberg	356/127
4,051,458	9/1977	Morton	340/146.3 AG
4,282,548	8/1981	Plummer	358/107

Primary Examiner—Stephen C. Buczinksi
Assistant Examiner—Linda J. Wallace
Attorney, Agent, or Firm—Bobby D. Scearce; Donald J. Singer

[57] **ABSTRACT**

A method of measuring optical properties of a transparency uses a video camera for focusing and then refocusing an image of a point source of light transmitted through a test region when the transparency is first absent and then later present at the test region. The distance the camera needs to be moved together with the focal length of a focusing lens used in carrying out the method provide sufficient quantitative data to calculate the spherical optical power of the transparency. Also, the camera generates video images of the point source both before and after the transparency is present in the test region. These images are displayed on a screen containing a grid pattern which facilitates measurement of the displacement of the image from the center of the grid or from the optical axis due to the presence of prismatic deviation in the transparency. Given the earlier data and supplemented by the latter displacement quantity, the prismatic deviation of the transpareny can also be calculated.

5 Claims, 2 Drawing Figures



United States Patent [19]

Task et al.

[11] **Patent Number:** **4,687,338**

[45] **Date of Patent:** **Aug. 18, 1987**

[54] **METHOD OF MEASUREMENT OF HAZE IN TRANSPARENCIES**

[75] Inventors: **Harry L. Task**, Dayton; **Louis V. Genco**, Enon, both of Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **463,191**

[22] Filed: **Feb. 2, 1983**

[51] Int. Cl.[4] **G01N 21/47**

[52] U.S. Cl. **356/446; 356/237**

[58] Field of Search 356/337, 338, 340, 342, 356/445, 446, 447, 448, 215, 221, 236, 237; 250/562, 572

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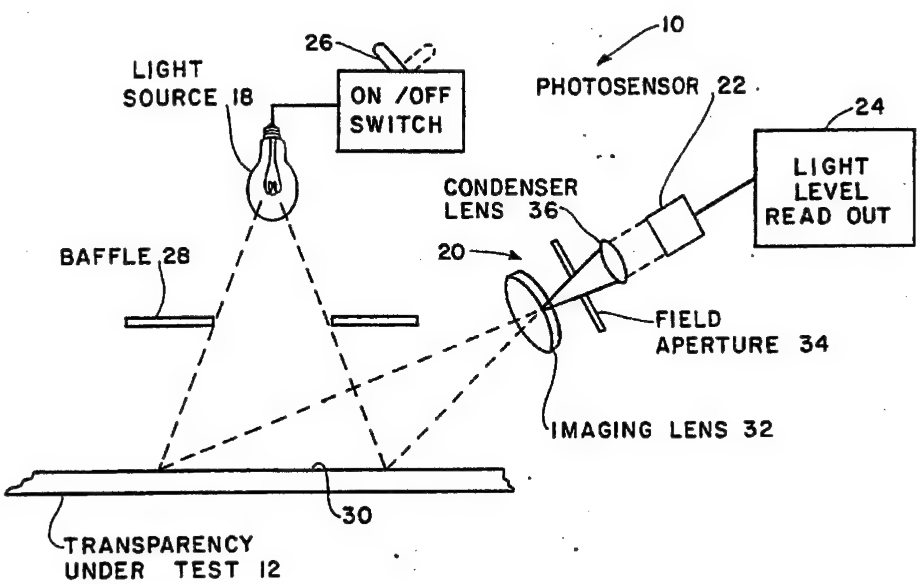
Primary Examiner—Bruce Y. Arnold

Attorney, Agent, or Firm—Fredric L. Sinder; Donald J. Singer; John R. Flanagan

[57] **ABSTRACT**

A method of measuring haze of an aircraft transparency includes producing a first reading representative of the level of light scattered by an area of a transparency under test while on the aircraft when it is illuminated by a known light source, and producing a second reading representative of the level of light scattered by a predetermined, preferably worst haze condition, reference plate when it is illuminated by the light source in place of the transparency. Then, a ratio of the first and second readings is calculated to provide a quantitative measure proportional to the degree of haze in the transparency test area.

10 Claims, 2 Drawing Figures



United States Patent [19]

Task

[11] **Patent Number: 4,946,282**

[45] **Date of Patent: Aug. 7, 1990**

[54] **TRANSPARENCY TRANSMISSIVITY MEASUREMENT DEVICE**

[75] Inventor: **Harry L. Task**, Dayton, Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **273,309**

[22] Filed: **Nov. 18, 1988**

[51] **Int. Cl.**[5] **G01N 21/59**; G01N 21/84

[52] **U.S. Cl.** **356/432**; 356/443

[58] **Field of Search** 356/432, 434, 443, 236; 250/228, 571

[56] **References Cited**

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4,623,258	11/1986	Task et al.	356/432

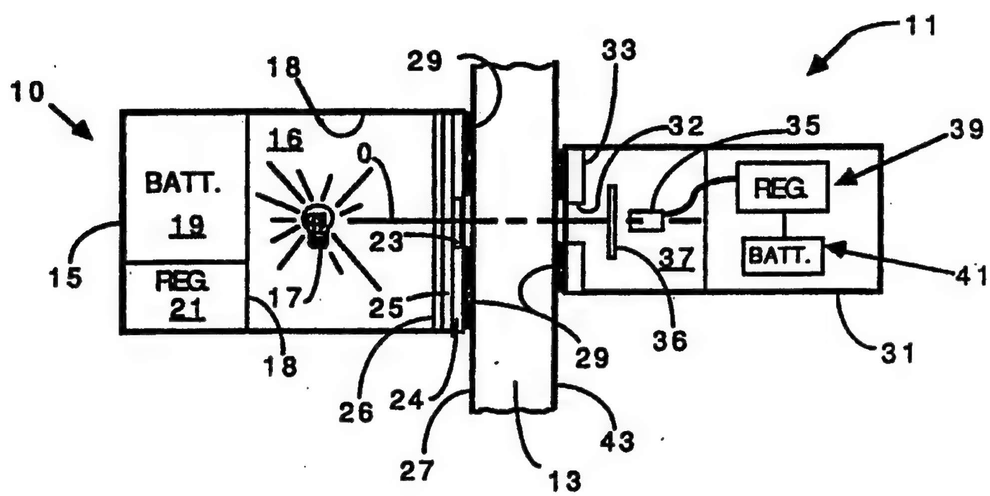
Primary Examiner—Vincent P. McGraw

Attorney, Agent, or Firm—Bobby D. Scearce; Donald J. Singer

[57] **ABSTRACT**

A device for measuring optical transmissivity of a transparency is described which comprises a diffuse light source (Lambertian diffuser) of controllable substantially constant luminance and preselected light emitting surface area for placement near a first side of a transparency for transmitting diffuse light along an optical axis through the transparency, a housing having a wall defining an aperture for placement near the second side of the transparency opposite the diffuse light source, and a detector in the form of a photo diode, cadmium sulfide cell or the like disposed within the housing and coaxial with and spaced a preselected distance from the aperture, the aperture being selected in size to expose all of the effective light detection surface area of said detector to the light emitting surface area of the diffuse light source.

21 Claims, 2 Drawing Sheets



United States Patent [19]

Task

[11] **Patent Number:** 5,059,023

[45] **Date of Patent:** Oct. 22, 1991

[54] **ANGULAR DEVIATION MEASUREMENT SYSTEM**

[75] Inventor: **Harry L. Task**, Dayton, Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **374,121**

[22] Filed: **Jun. 23, 1989**

[51] **Int. Cl.^{5}** **G01N 21/88**; G01B 11/30

[52] **U.S. Cl.** **356/239**; 356/371

[58] **Field of Search** 356/73.1, 309, 320, 356/239, 351, 407, 414, 327

[56] **References Cited**

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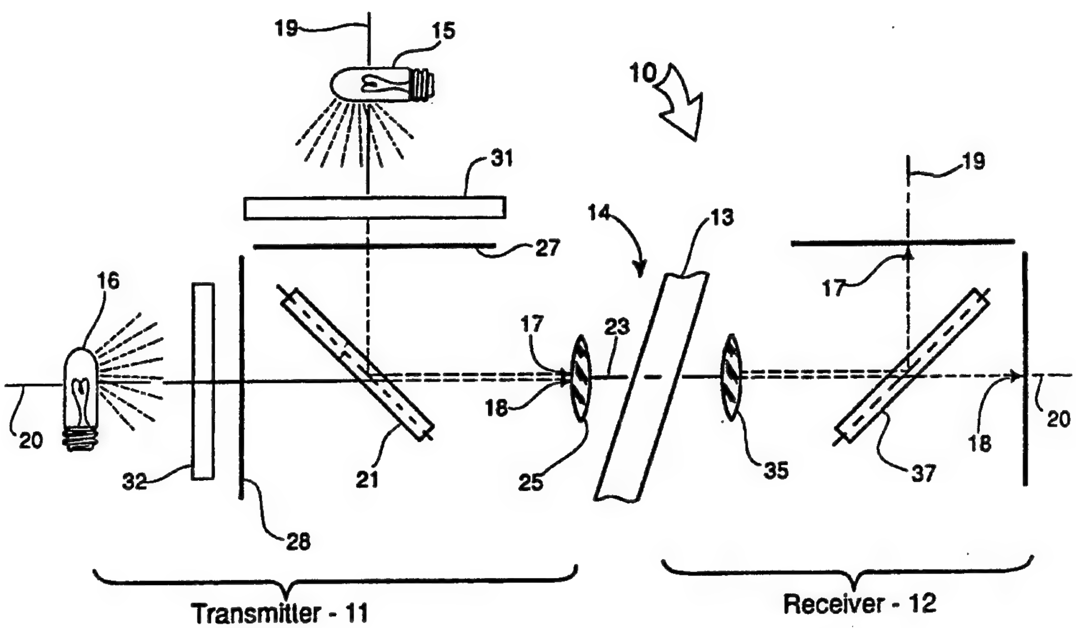
Primary Examiner—Vincent P. McGraw
Assistant Examiner—LaCharles P. Keesee
Attorney, Agent, or Firm—Bobby D. Scearce; Donald J. Singer

[57] **ABSTRACT**

A system for measuring optical angular deviation in a transparency such as an aircraft or automobile windscreen, visor, optical lens or the like is described wherein orthogonal first and second incoherent light line images are combined and separately optically encoded, such as by wavelength or by polarization vector using suitable color or polarization filters or beamsplitters, and projected through a transparency under examination, the combined images then separated to detect simultaneously and separately the vertical and horizontal components of angular deviation at a specific location in the transparency.

6 Claims, 3 Drawing Sheets



United States Statutory Invention Registration [19]

[11] Reg. Number: H999

Merkel et al. [43] Published: Dec. 3, 1991

[54] TRANSPARENCY DISTORTION MEASUREMENT PROCESS

[75] Inventors: Harold S. Merkel, Beavercreek; Harry L. Task, Dayton, both of Ohio

[73] Assignee: The United States of America as represented by the Secretary of the Air Force, Washington, D.C.

[21] Appl. No.: 582,463

[22] Filed: Sep. 13, 1990

[51] Int. Cl.^{5} G01N 21/17

[52] U.S. Cl. 356/239; 358/106; 364/507; 364/552; 382/8; 250/563; 250/572

[58] Field of Search 356/239, 384, 387; 250/563, 572; 358/106; 364/525, 507, 552; 382/1, 8, 16, 18

[56] References Cited

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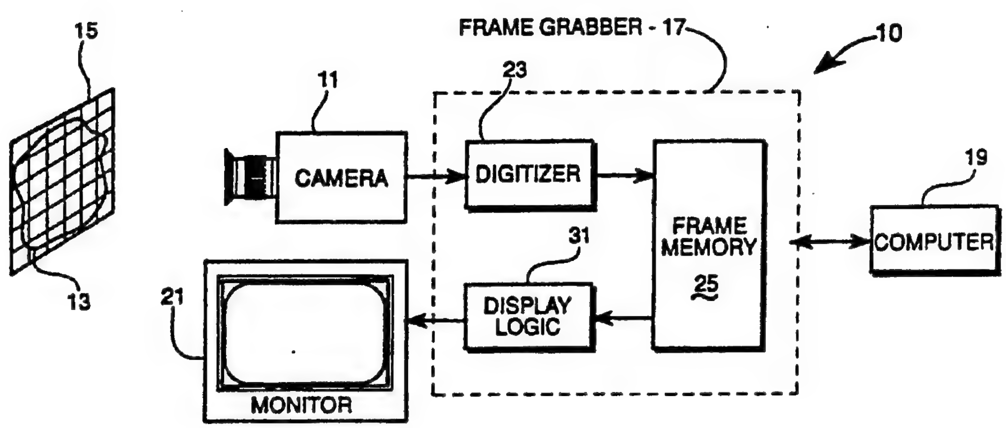
Primary Examiner—Bernarr E. Gregory
Attorney, Agent, or Firm—Bobby D. Scearce

[57] ABSTRACT

A method for measuring optical distortion in a transparency is described which comprises the steps of acquiring an analog image of a grid board through the transparency, digitizing the analog image to form a digitized image comprising a multiplicity of pixels defining the shape of the grid board as viewed through the transparency, locating on the digitized image the pixels defining the grid and determining optical distortion of the transparency by comparing the shape of the grid in the digitized image to the actual grid shape on the grid board.

6 Claims, 1 Drawing Sheet



United States Patent [19]

Pinkus

[11] **Patent Number: 5,070,239**

[45] **Date of Patent: Dec. 3, 1991**

[54] **NIGHT VISION GOGGLE AMBIENT ILLUMINATION TESTING**

[75] Inventor: **Alan R. Pinkus**, Oxford, Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **608,932**

[22] Filed: **Nov. 5, 1990**

[51] **Int. Cl.**[5] **G01J 1/42**; G01D 18/00

[52] **U.S. Cl.** .... **250/252.1**; 250/504 R

[58] **Field of Search** .... 250/252.1 A, 330, 332, 250/331, 493.1, 504 R, 504 H; 358/113

[56] **References Cited**

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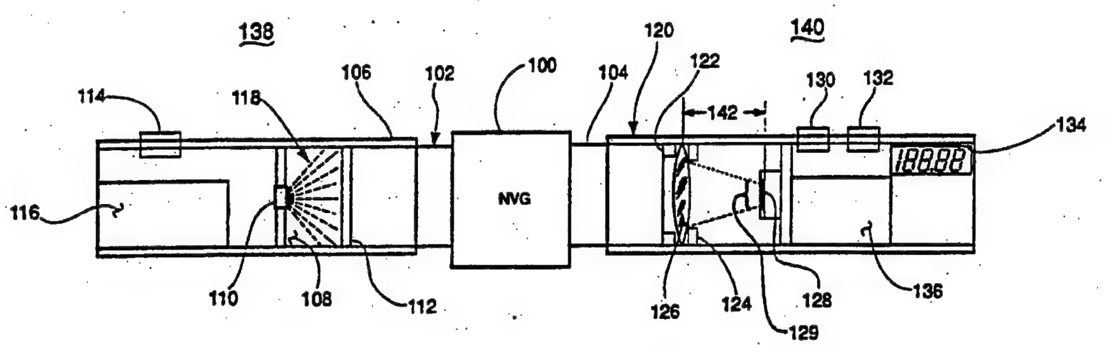
Primary Examiner—Constantine Hannaher
Assistant Examiner—Edward J. Glick
Attorney, Agent, or Firm—Gerald B. Hollings; Donald J. Singer

[57] **ABSTRACT**

A night vision goggle capability evaluation apparatus useful in assessing the degree of illumination present in a proposed NVG operating environment is disclosed. The evaluation apparatus includes portable illuminator and detector devices that are battery operated and optionally coupled to the input and output ports of the goggle during both their own calibration and during measurement of the proposed operating environment. The disclosed apparatus operates by calibrating the NVG output measuring detector from the saturated and dark output extremes of the NVG system and then using this calibrated detector to measure the output of the NVG system and determine whether is it receiving adequate light for satisfactory performance.

8 Claims, 1 Drawing Sheet



United States Patent [19]

Task

[11] **Patent Number:** 5,187,541

[45] **Date of Patent:** Feb. 16, 1993

[54] **SINGLE BEAM ANGULAR DEVIATION MEASUREMENT SYSTEM AND METHOD**

[75] Inventor: Harry L. Task, Dayton, Ohio

[73] Assignee: The United States of America as represented by the Secretary of the Air Force, Washington, D.C.

[21] Appl. No.: 726,066

[22] Filed: Jul. 5, 1991

[51] Int. Cl.[5] G01N 21/00

[52] U.S. Cl. 356/239

[58] Field of Search 356/128, 138, 239, 127, 356/237, 129

[56] **References Cited**

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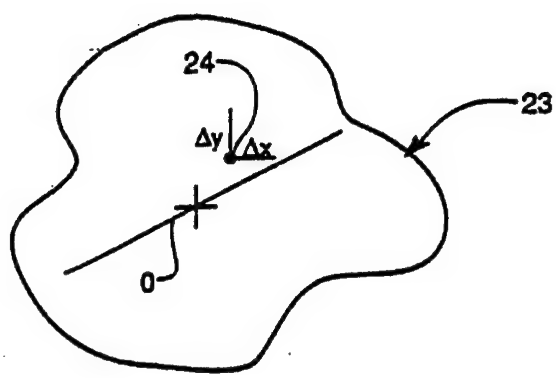
4,377,341	3/1983	Task et al.	356/239
4,398,822	8/1983	Task	356/239

Primary Examiner—F. L. Evans
Assistant Examiner—K. P. Hantis
Attorney, Agent, or Firm—Bobby D. Scearce; Donald J. Singer

[57] **ABSTRACT**

System and method for measuring angular deviation in a transparency are described which comprise the steps of directing a large diameter collimated beam of light along an optical axis through a transparency, focusing a portion of the collimated beam, determining the position of the focus of the beam portion relative to the axis, repeating the above steps without the transparency, measuring any difference in position of the focus with and without the transparency, and calculating the vertical and horizontal components of angular deviation in the transparency according to relationships disclosed.

4 Claims, 2 Drawing Sheets



United States Patent [19]

Task

[11] **Patent Number:** **5,557,403**

[45] **Date of Patent:** **Sep. 17, 1996**

[54] **SYSTEM AND METHOD FOR MEASURING CRAZING IN A TRANSPARENCY**

[75] Inventor: **Harry L. Task**, Dayton, Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **415,407**

[22] Filed: **Apr. 3, 1995**

[51] **Int. Cl.**^{6} **G01N 21/00**

[52] **U.S. Cl.** **356/239**; 356/240; 356/124; 356/146

[58] **Field of Search** 356/239, 240, 356/237, 124, 446

[56] **References Cited**

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Primary Examiner—Frank Gonzalez

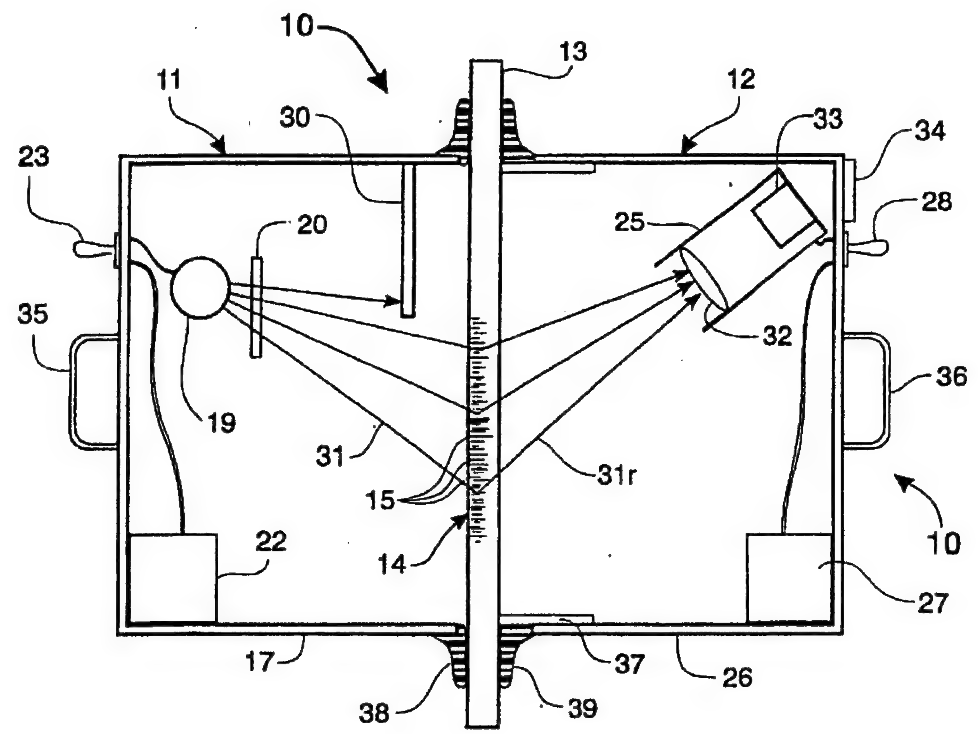
Assistant Examiner—Reginald A. Ratliff

Attorney, Agent, or Firm—Bobby D. Scearce; Thomas L. Kundert

[57] **ABSTRACT**

A system for measuring crazing in a transparency is described which comprises one or more light sources disposed near a first surface of the transparency for projecting light rays through the transparency at the portion thereof having a crazed condition, optical detectors corresponding in number to the number of light sources disposed on the opposite side of the transparency, each detector positioned to detect only light from a single corresponding source reflected from the crazed portion of the transparency, and a source of power for the sources and detectors. A sequencing circuit may be included to selectively activate selected light sources and corresponding optical detectors.

8 Claims, 2 Drawing Sheets



United States Statutory Invention Registration [19]

[11] Reg. Number: H1655

Task

[45] Published: Jun. 3, 1997

[54] **BACKSCATTER HAZE MEASUREMENT USING A DISTRIBUTED LIGHT SOURCE**

[75] Inventor: **Harry L. Task**, Dayton, Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **416,600**

[22] Filed: **Apr. 4, 1995**

[51] **Int. Cl.**^{6} **G01N 21/47**

[52] **U.S. Cl.** **356/446**

[58] **Field of Search** 356/446

[56] **References Cited**

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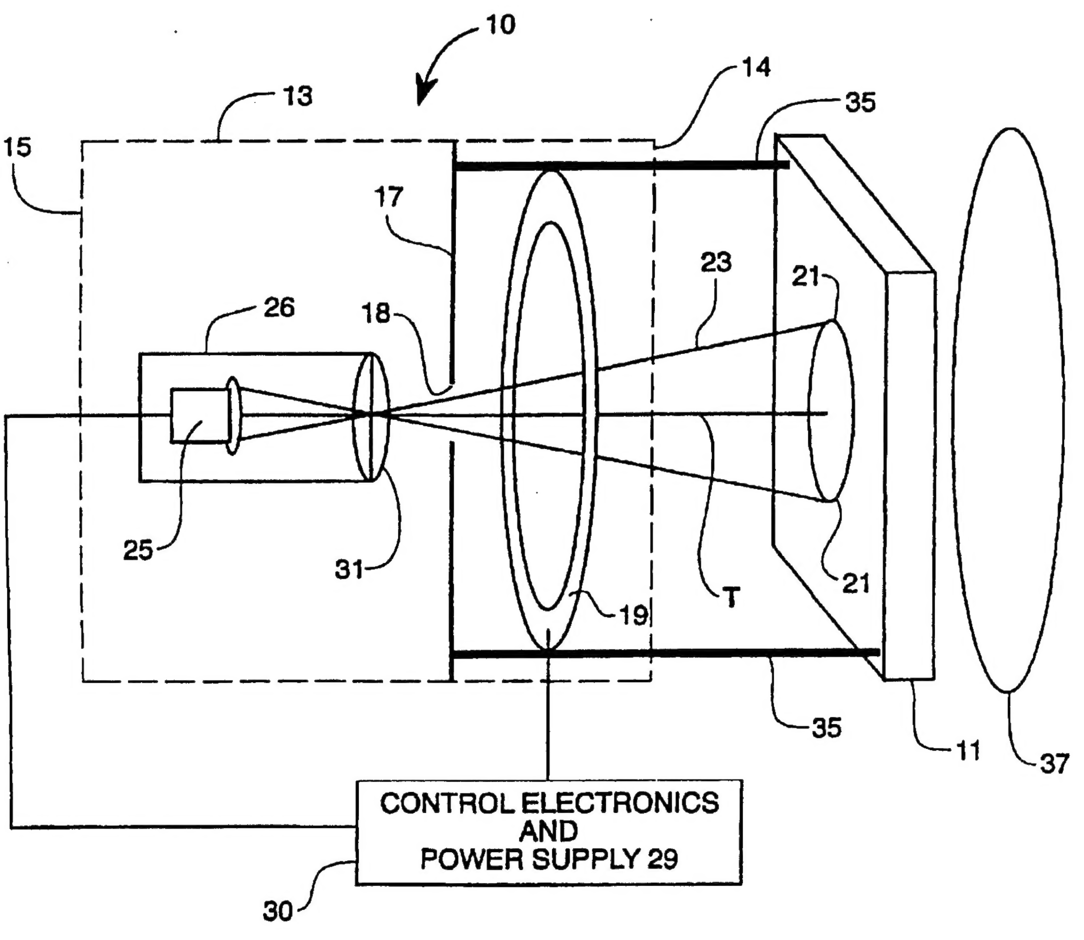
4,687,338	8/1987	Task et al.	356/446

Primary Examiner—Bernarr E. Gregory
Attorney, Agent, or Firm—Bobby D. Scearce; Thomas L. Kundert

[57] **ABSTRACT**

System and method for in situ measurement of haze in a transparency, such as an aircraft windscreen, canopies, windows or the like are described which comprise an annular light source for illuminating a selected test area of the transparency along a selected optical axis, a photodetector, and a lens for projecting an image of the illuminated test area along the axis onto the photodetector.

3 Claims, 1 Drawing Sheet



United States Patent [19]

Task et al.

[11] **Patent Number: 5,712,709**

[45] **Date of Patent: Jan. 27, 1998**

[54] **HAZE AND TRANSMISSIVITY MEASUREMENTS**

[75] Inventors: **Harry Lee Task; Peter Marasco**, both of Dayton, Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **630,712**

[22] Filed: **Apr. 8, 1996**

[51] **Int. Cl.**[6] **G01N 21/17; G01N 21/88**

[52] **U.S. Cl.** **356/432**; 356/435; 356/239

[58] **Field of Search** 356/432, 435, 356/443, 237, 239

[56] **References Cited**

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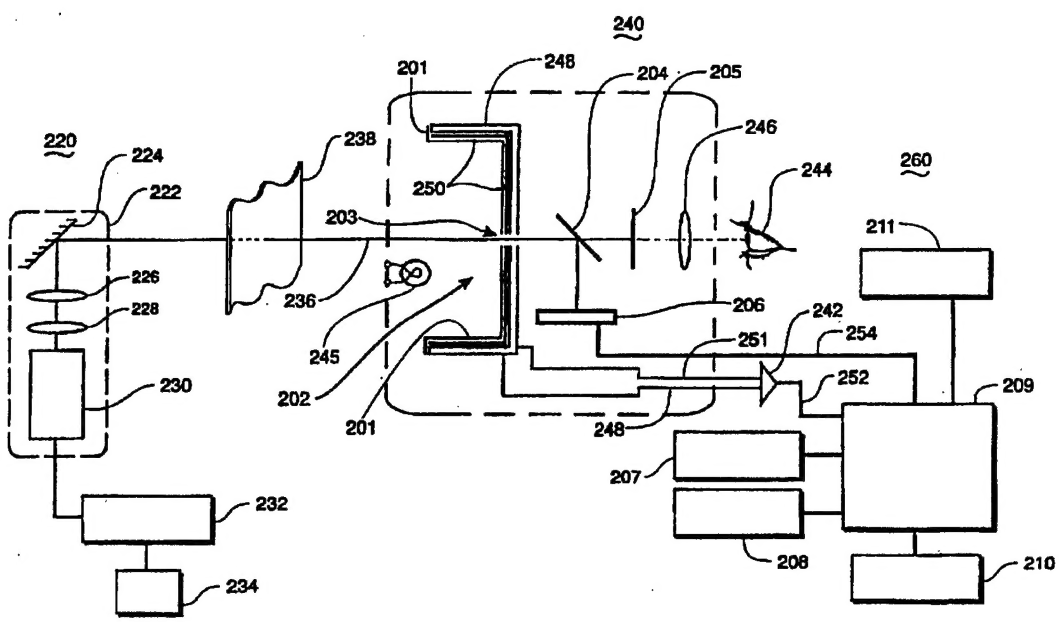
Primary Examiner—F. L. Evans
Attorney, Agent, or Firm—Gerald B. Hollins; Thomas L. Kundert

[57] **ABSTRACT**

A portable and potentially computer-controlled aircraft windscreen or the like test arrangement for quantitative determination of haze and energy transmissivity characteristics in the windscreen material. The test arrangement includes two portable transducer enclosures which lend to convenient use in tested aircraft environments and provides optical assistance in achieving a desired alignment of these transducer enclosures prior to testing. Improved sensitivity over prior haze evaluation arrangements is achieved through use of this accurate alignment and through capture of a large fraction of a haze generated optical signal with an efficient transducer configuration. The testing arrangement also includes optical filtering capability and laser signal modulation assistance in excluding ambient illumination interference with measurement-related optical signals. A plurality of use environments are contemplated including military and non-military uses.

20 Claims, 2 Drawing Sheets



(12) **United States Patent**
Task et al.

(10) **Patent No.: US 6,194,701 B1**
(45) **Date of Patent: Feb. 27, 2001**

(54) **PORTABLE NIGHT VISION GOGGLE HAZE AND TRANSMISSIVITY MEASUREMENT DEVICE**

(75) Inventors: **Harry L. Task**, Dayton; **Alan R. Pinkus**, Bellbrook; **Sheldon E. Unger**, Englewood, all of OH (US)

(73) Assignee: **The United States of Americas as represented by the Secretary of the Air Force**, Washington, DC (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/287,078**

(22) Filed: **Apr. 6, 1999**

(51) **Int. Cl.**[7] **G01N 21/59**; G01N 21/958

(52) **U.S. Cl.** .... **250/214 VT**; 356/432; 356/333

(58) **Field of Search** .... 250/214 VT, 216, 250/559.16, 559.17, 330, 333, 339.11, 341.8; 356/432, 433, 434, 435, 443, 445, 446, 447, 448, 337, 338

(56) **References Cited**

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4,687,338 * 8/1987 Task et al. 356/446
4,764,007 * 8/1988 Task et al. 351/243
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5,712,709 * 1/1998 Task et al. 356/432

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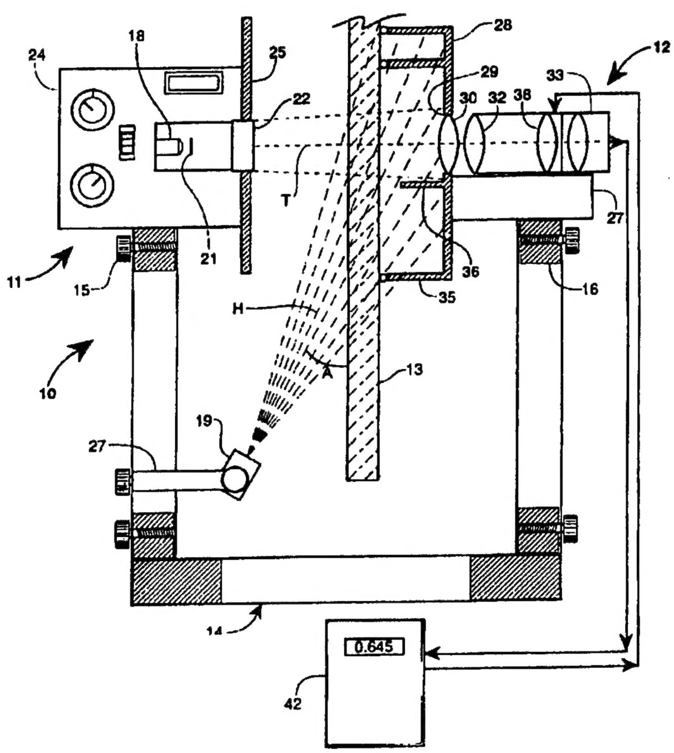
Primary Examiner—John R. Lee
(74) *Attorney, Agent, or Firm*—Bobby D. Searce; Thomas L. Kundert

(57) **ABSTRACT**

Device and method are described for measuring transmissivity and haze in transparencies as detected through night vision goggles, including an emitter portion and a sensor portion, the emitter portion including a first light source for presenting an image to the sensor portion through the transparency and a second light source for projecting a haze producing light onto the transparency, the sensor portion including a light intensifier tube and a photometer for measuring the luminance output of the light intensifier tube and quantifying attenuation (transmissivity) and haze (light scatter) characteristics of the transparency as viewed through night vision goggles.

6 Claims, 3 Drawing Sheets



(12) **United States Patent**
Pinkus et al.

(10) **Patent No.: US 6,401,589 B1**
(45) **Date of Patent: *Jun. 11, 2002**

(54) **LIMITING AIRBORNE TARGET DESIGNATING LASER CANOPY RETURNS**

(75) Inventors: **Alan R. Pinkus**, Bellbrook; **Harry L. Task**, Dayton; **Peter L. Marasco**, Kettering, all of OH (US)

(73) Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, DC (US)

(*) Notice: This patent issued on a continued prosecution application filed under 37 CFR 1.53(d), and is subject to the twenty year patent term provisions of 35 U.S.C. 154(a)(2).

Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/501,290**

(22) Filed: **Feb. 9, 2000**

(51) **Int. Cl.**[7] **F41F 5/00**
(52) **U.S. Cl.** **89/1.1**
(58) **Field of Search** 244/129.3; 89/1.11

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Primary Examiner—Charles T. Jordan
Assistant Examiner—Jordan M. Lofdahl
(74) *Attorney, Agent, or Firm*—Gerald B. Hollins; Thomas L. Kundert

(57) **ABSTRACT**

A laser energy window arrangement especially usable in a tactical aircraft having night vision equipment-aided cockpit visual information input requirements. The laser energy window arrangement enables use of laser apparatus directed external to the aircraft for target designation or other purposes while minimizing the amount of energy from such laser returning spuriously inside the cockpit where it inherently acts a noise signal for night vision equipment. The laser energy window limits the portion of the aircraft windshield or canopy exposed to laser radiation and its effects to a relatively small area, an obscurable area generating significantly reduced amounts of spurious return energy in comparison with use of the laser directly through an unlimited windshield, canopy, or other type of transparency. Transmission of spurious return energy from the laser energy window to remaining portions of the windshield or canopy is precluded by interruption of transmission paths within the windshield or canopy material and transducing the interrupted path energy into heat dissipated within or outside of the aircraft and not affecting the remainder of the canopy. Potentially increased aircraft to target standoff range, reduce need for aircrew use of laser eye protection gear, reduced laser induced windshield or canopy degradation and other benefits are identified for aircraft uses of the invention. Use of the window invention in other non aircraft and non military aircraft settings is also contemplated.

15 Claims, 5 Drawing Sheets